New Oscillation Results From MiniBooNE

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Outline

- Introduction
- MiniBooNE exp.
- Data analysis
- Results
- Future outlook
- Conclusion

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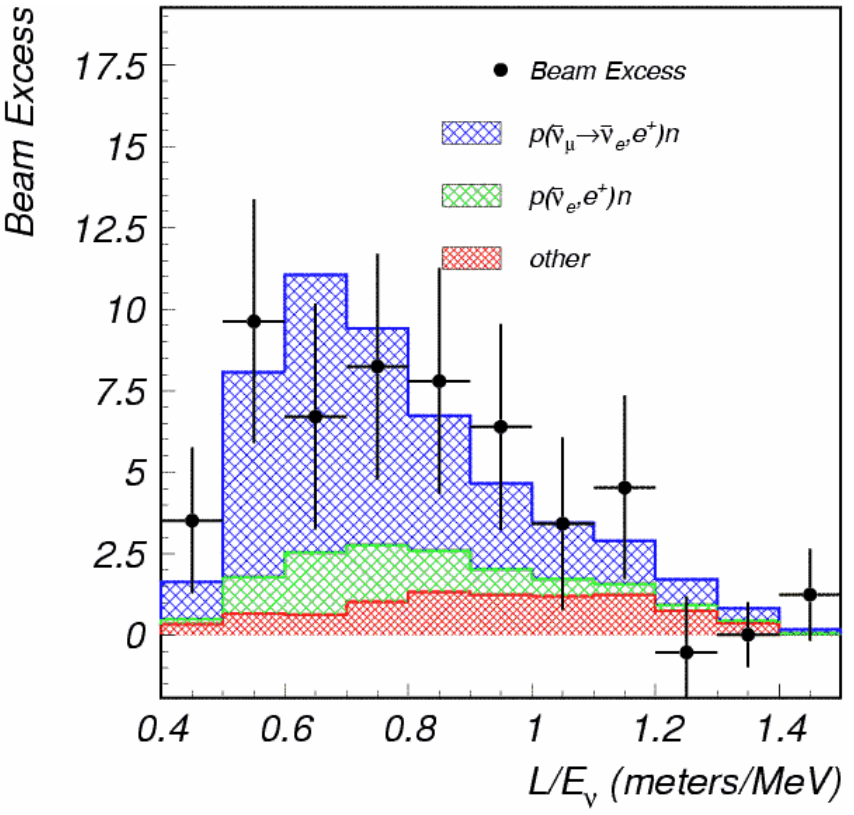
(The MiniBooNE Collaboration)

MiniBooNE motivation

- LSND experiment
- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)

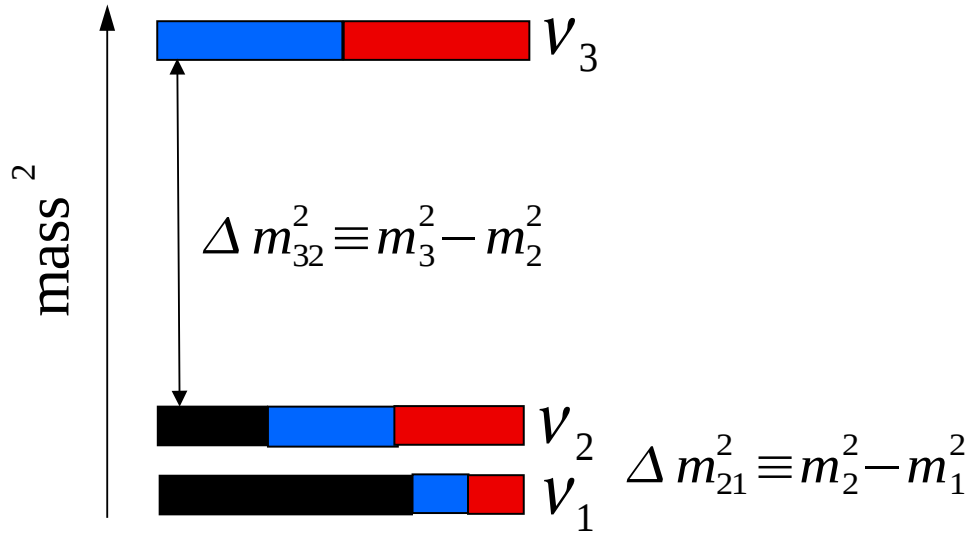


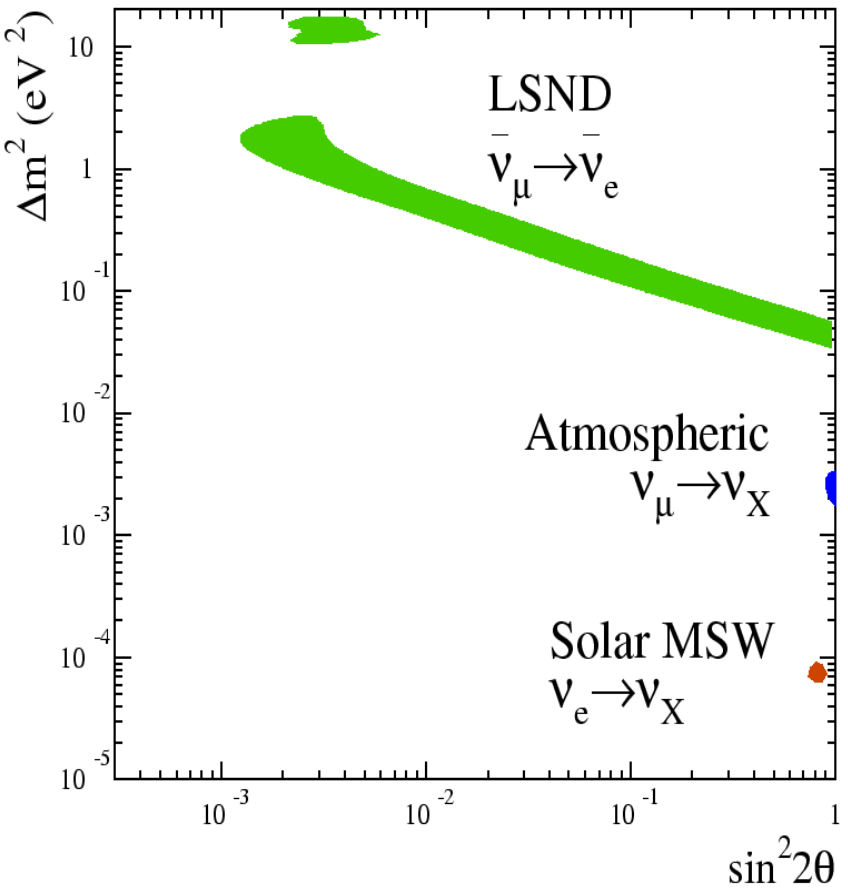
LSND signal

- Assuming two neutrino oscillations

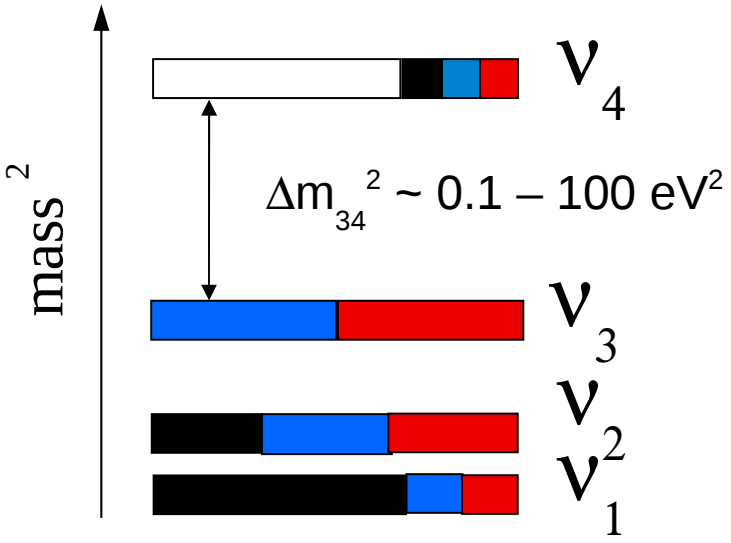
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings





Sterile neutrinos



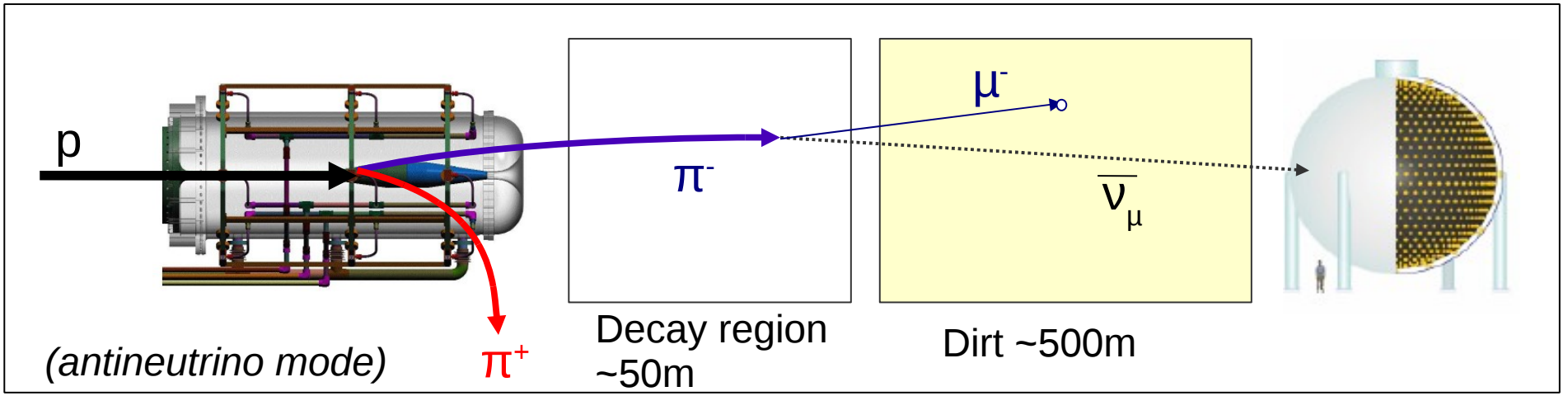
- Can have only 3 light active neutrinos
- 3 active neutrinos + 1 sterile neutrino

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2(1.27\,\Delta m^2_{41} L/E)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$$

- Model predicts same oscillation probability for neutrinos and anti-neutrinos

MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

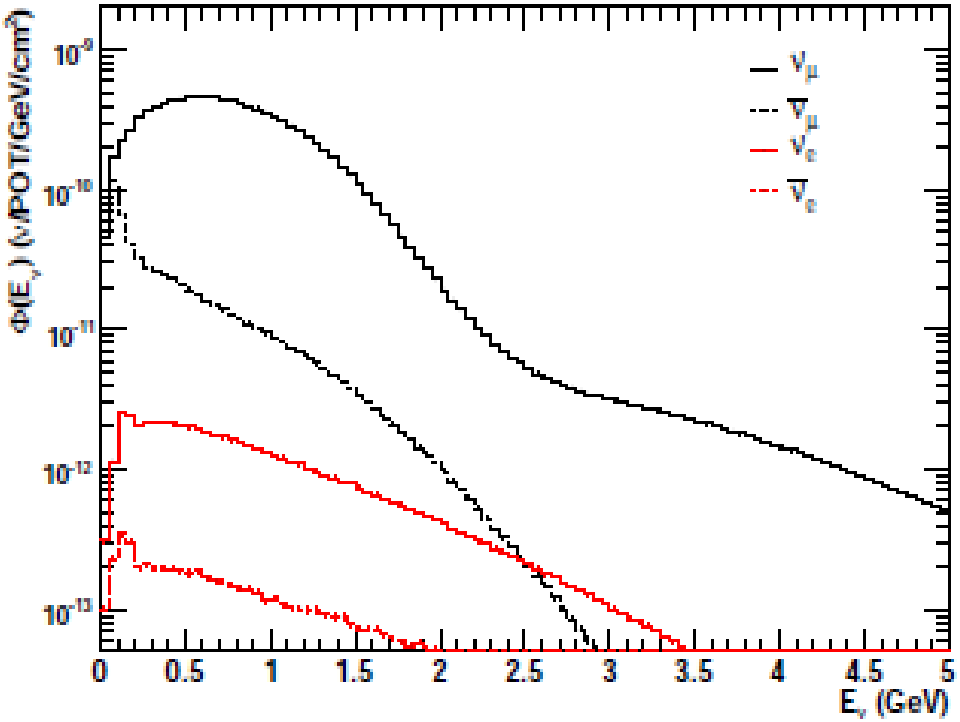
Neutrino flux

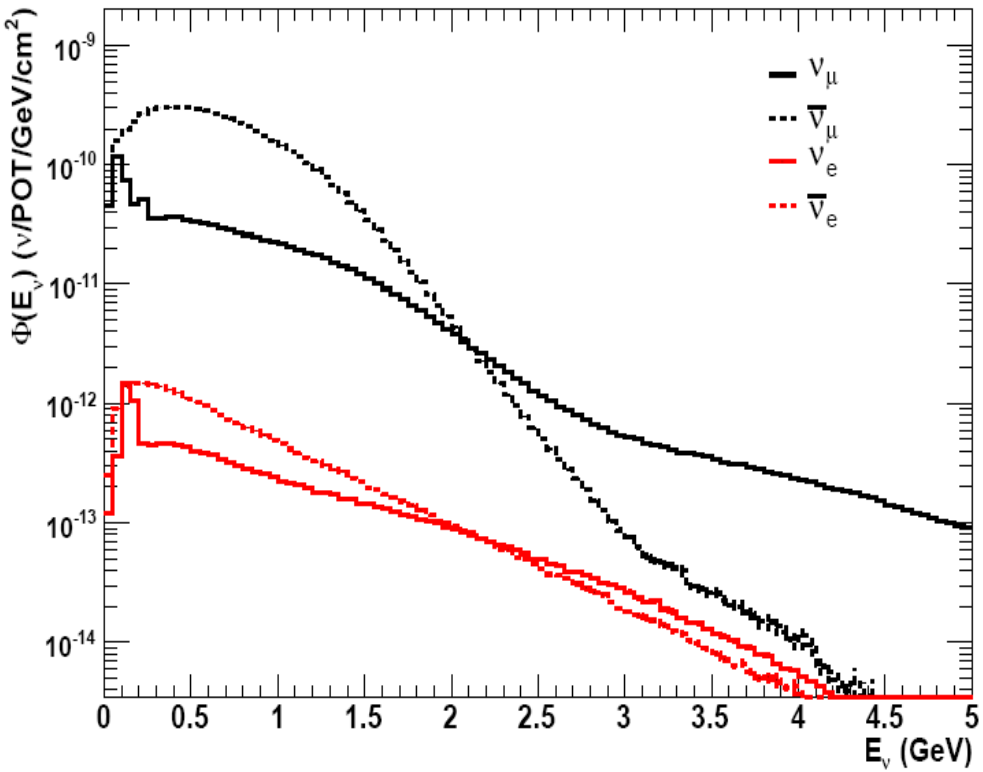
- Neutrino mode

ν_μ	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%

- Anti-neutrino mode

ν_μ	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%

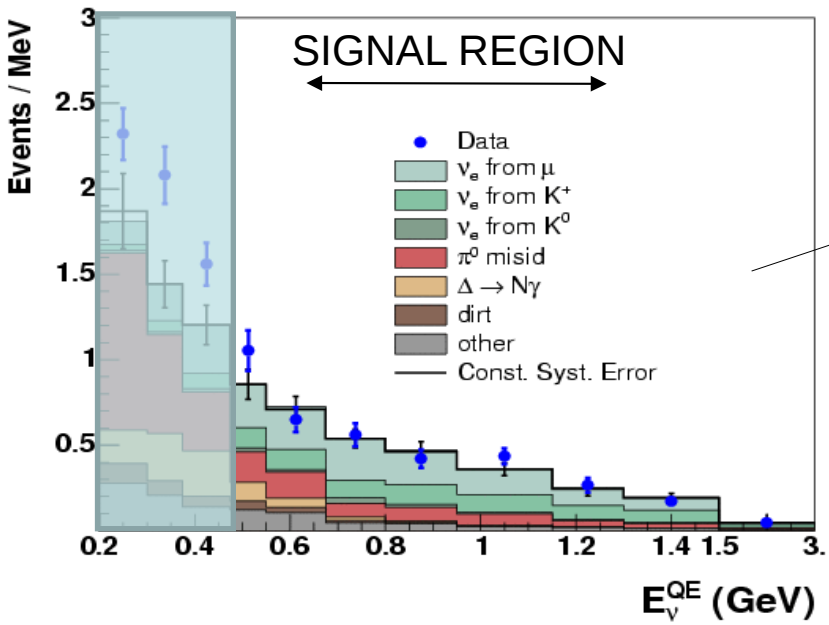


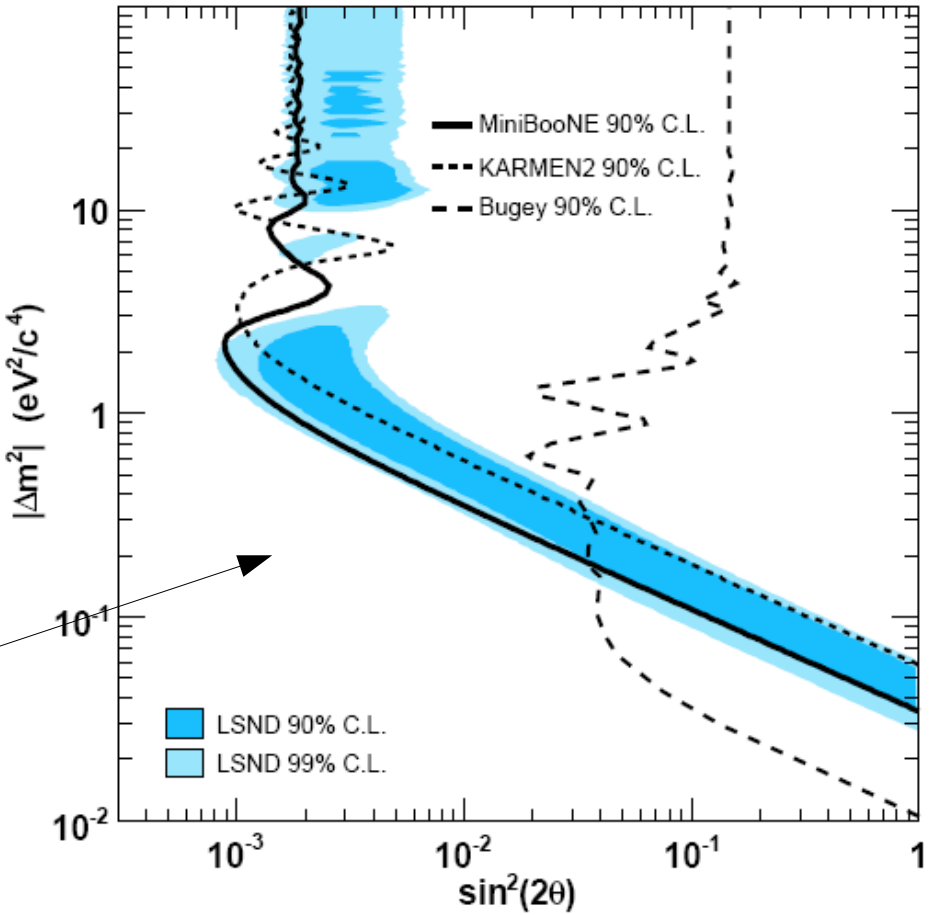


Phys. Rev. D79, 072002 (2009)

MiniBooNE neutrino result

- 6.5e20 POT
- No excess of events in signal region (E>475 MeV)
- Ruled out 2 ν oscillation as LSND explanation (assuming no CP or CPT violation)





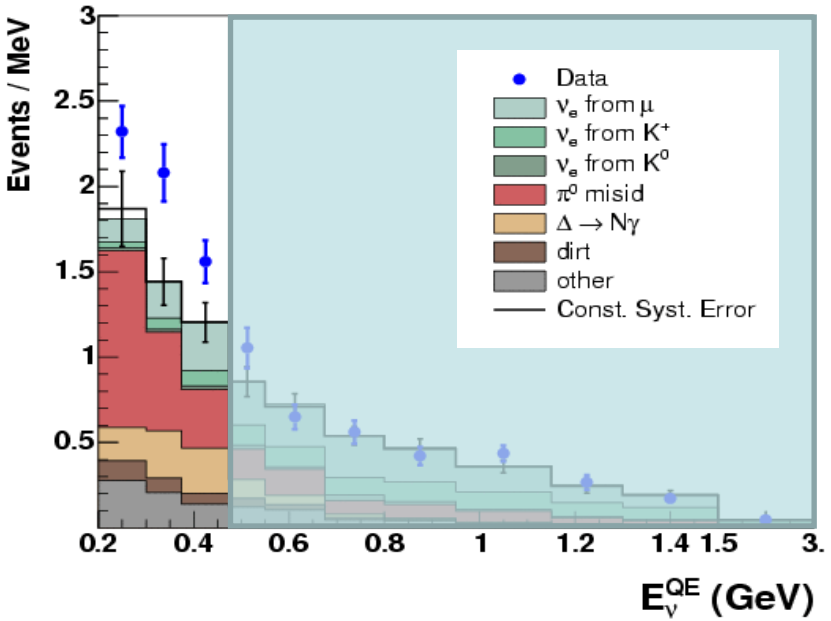
Phys. Rev. Lett. 98, 231801 (2007)

MiniBooNE neutrino result

Excess of events observed at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)

Shape not consistent with 2 ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

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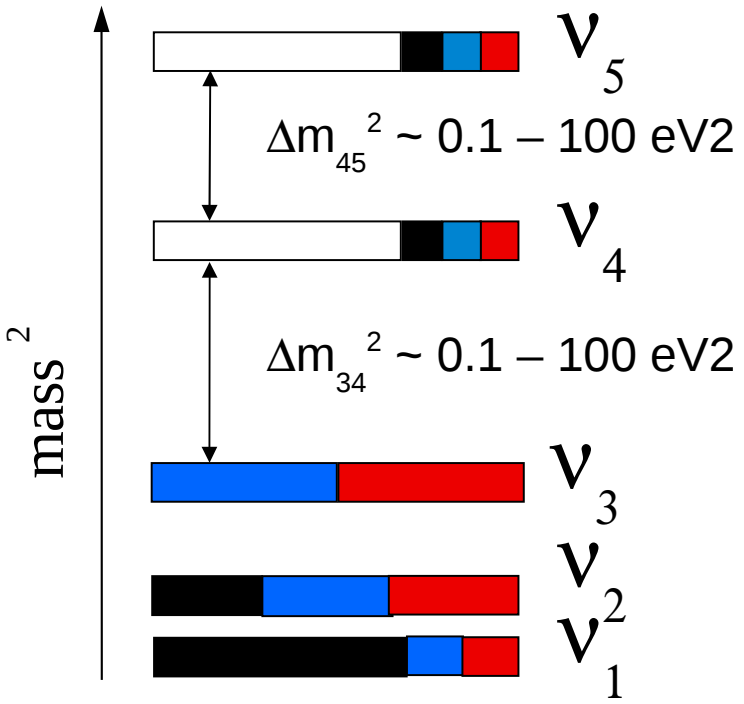
More sterile neutrinos



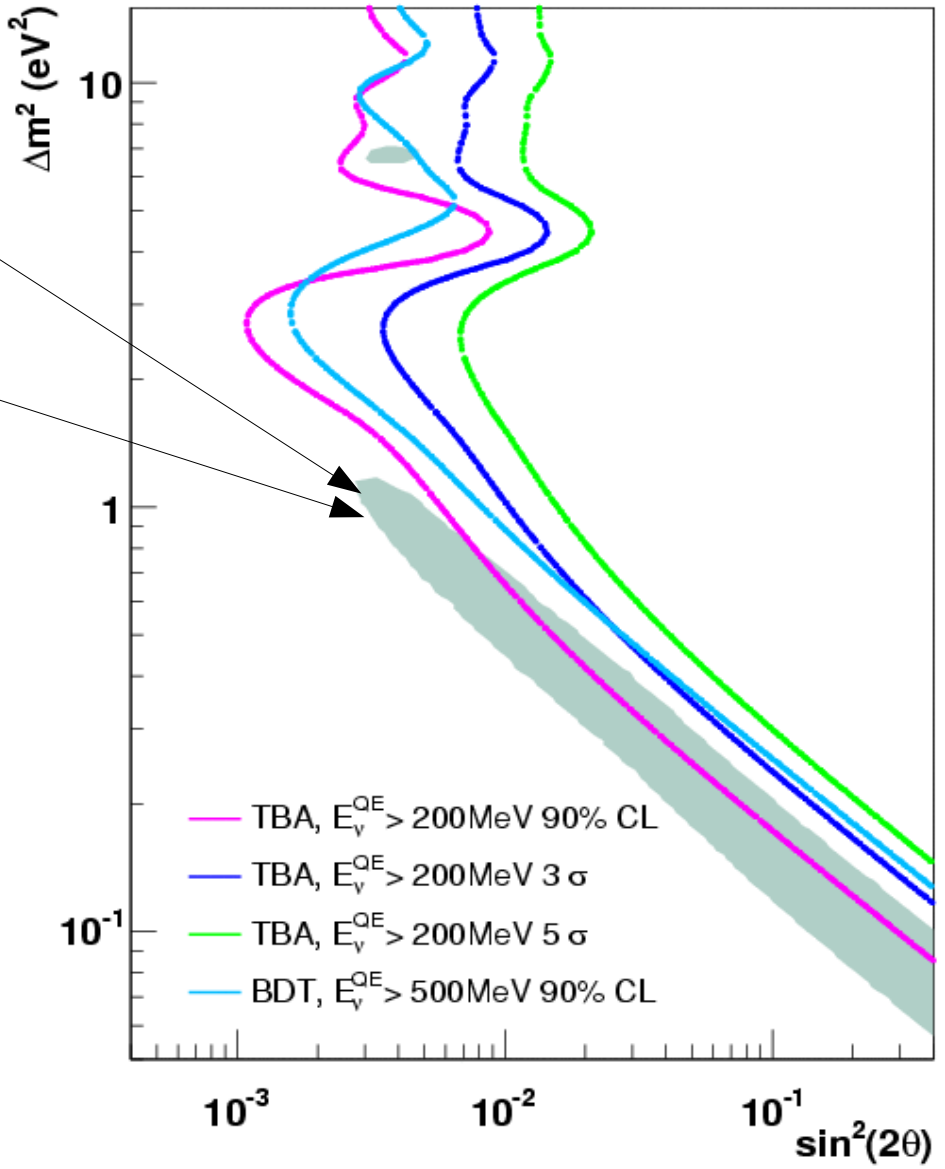
- Next minimal extension 3+2 models
- Favored by fits to appearance data (hep-ph/0705.0107)
- Model allows CP violation
  - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Anti-neutrino results

- LSND - signal
- Karmen – no signal
- MiniBooNE analysis of 3.4e20 POT

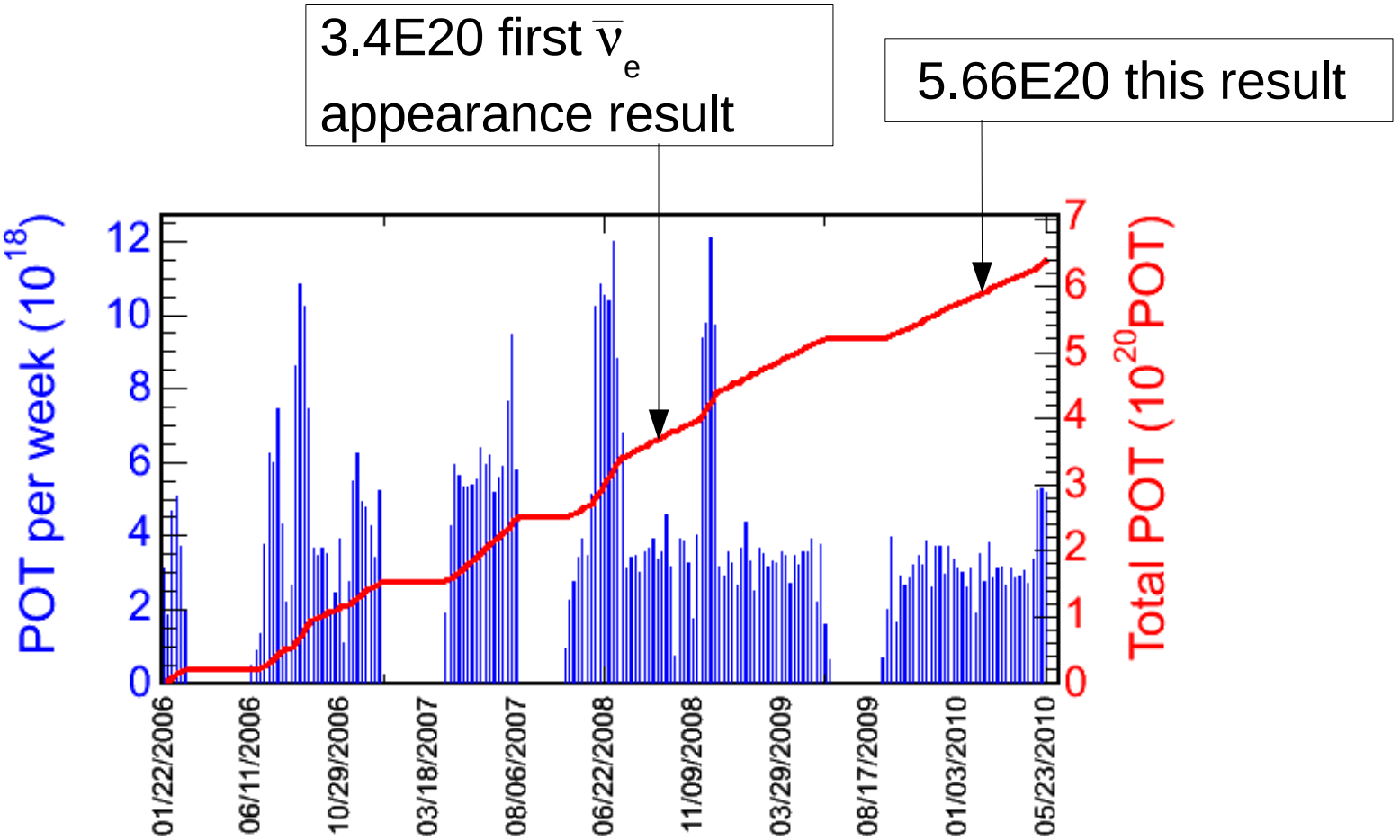
  (Phys. Rev. Lett. 103, 111801 (2009))

  - Inconclusive result



POT collection

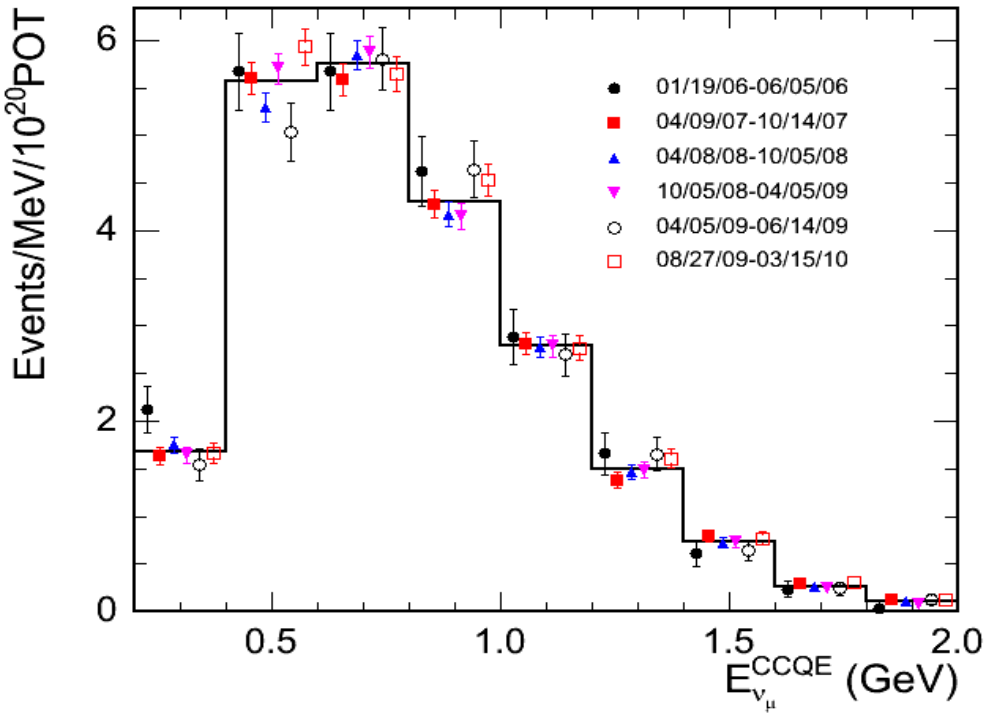
- Protons on target in anti-neutrino mode

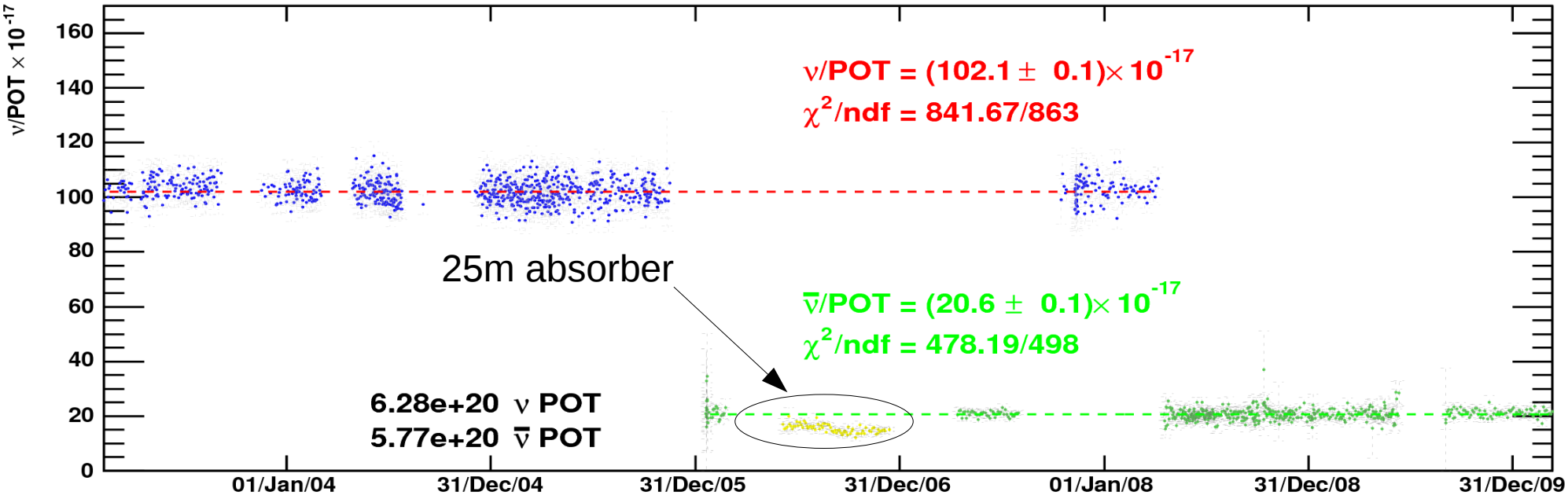


Thanks to Accelerator Division on all the POT!

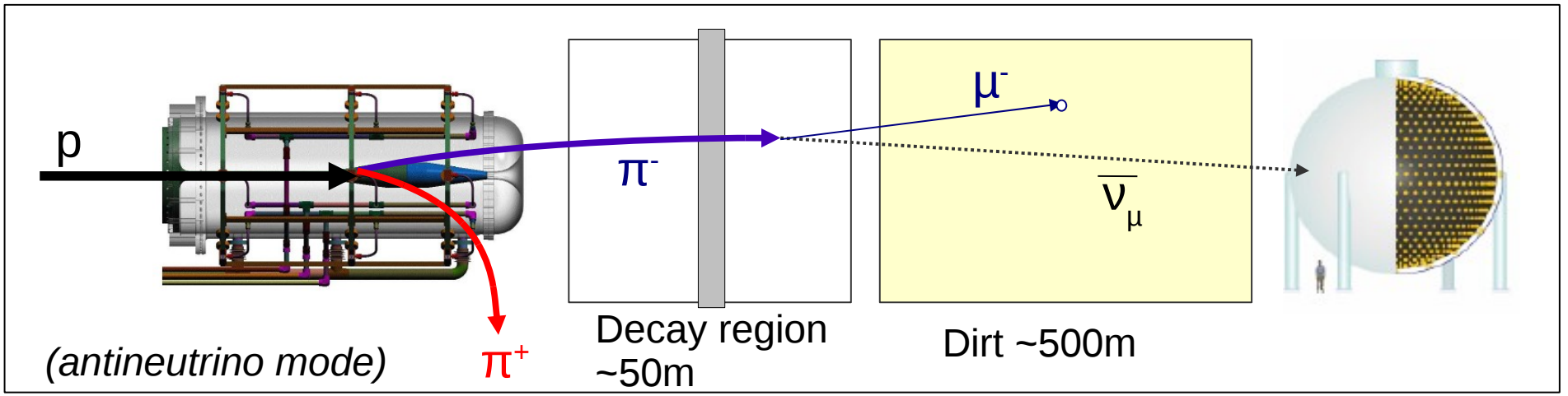
Data stability

- Very stable throughout the run





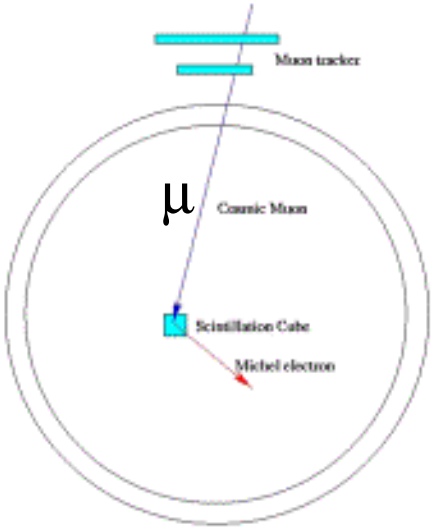
25m Absorber

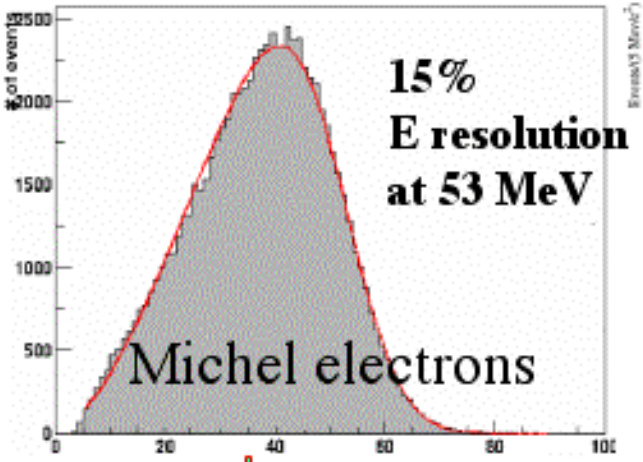


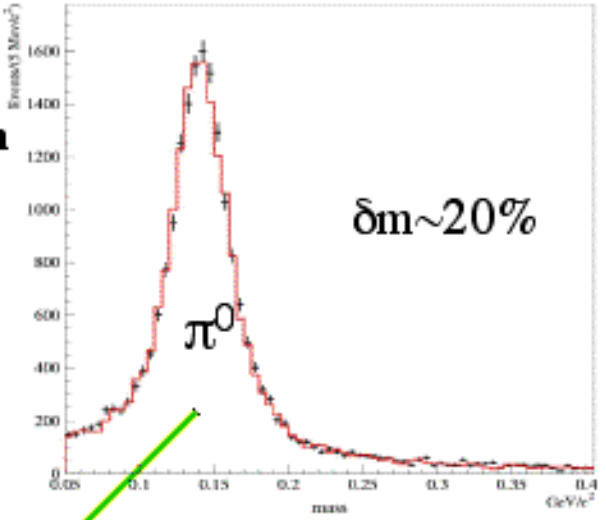
- Two periods of running with 1 & 2 absorber plates
  - 1 absorber plate - 0.569E20 POT
  - 2 absorber plates - 0.612E20 POT
- Good data/MC agreement ih high statistics samples (ν_μ CCQE, NC π^0, ...)
- Data included in this analysis

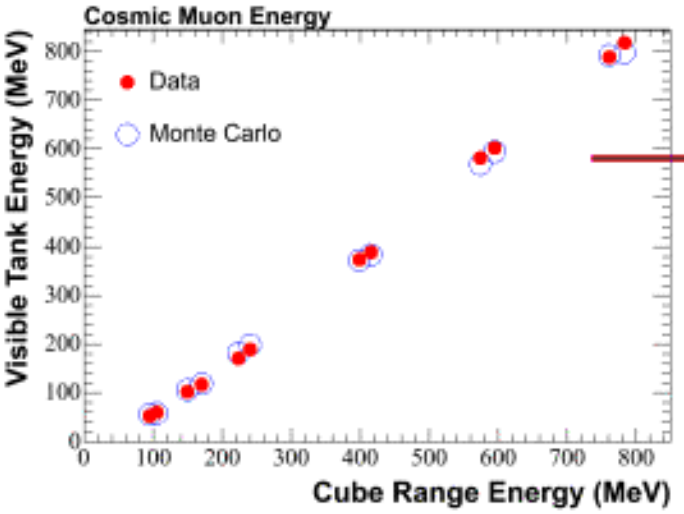
Calibration Sources

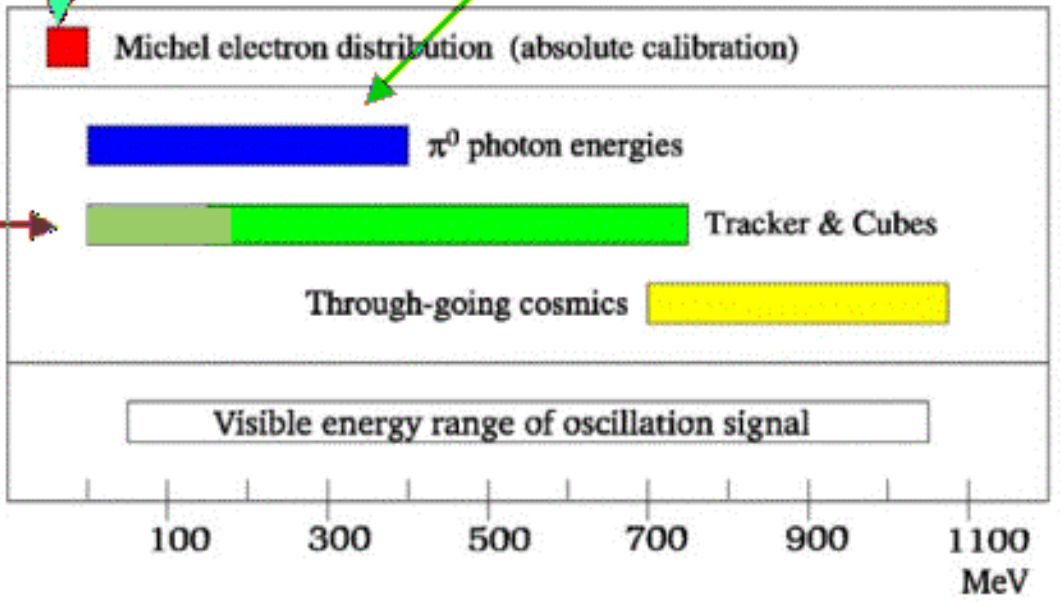
Tracker system





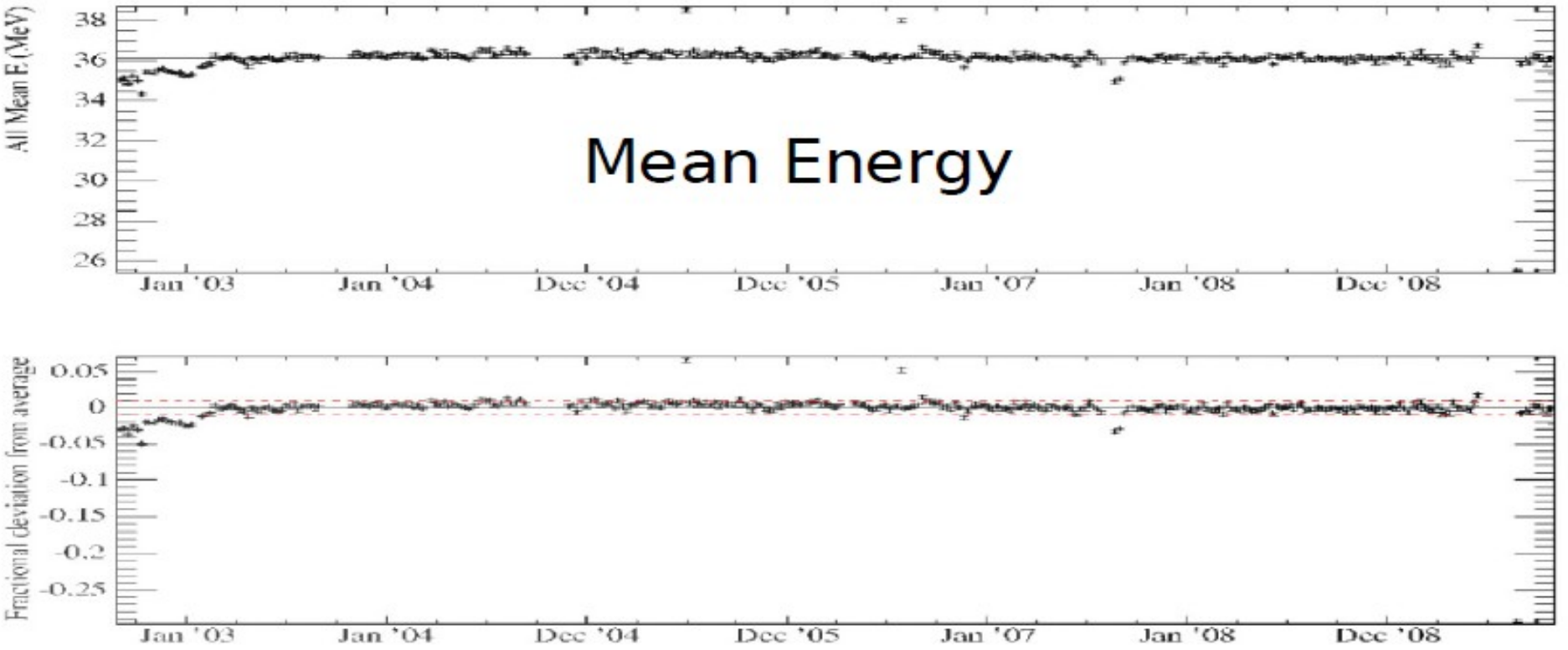






Detector calibration

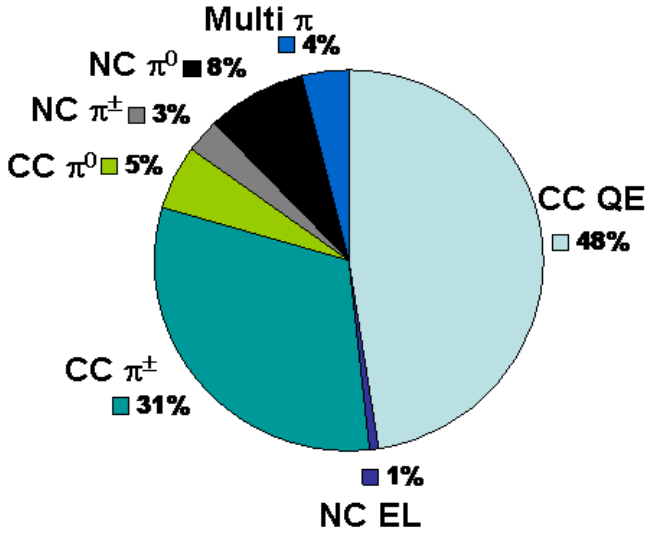
- Very stable
- For example: Michel electron mean energy within 1% since beginning of run (2002)

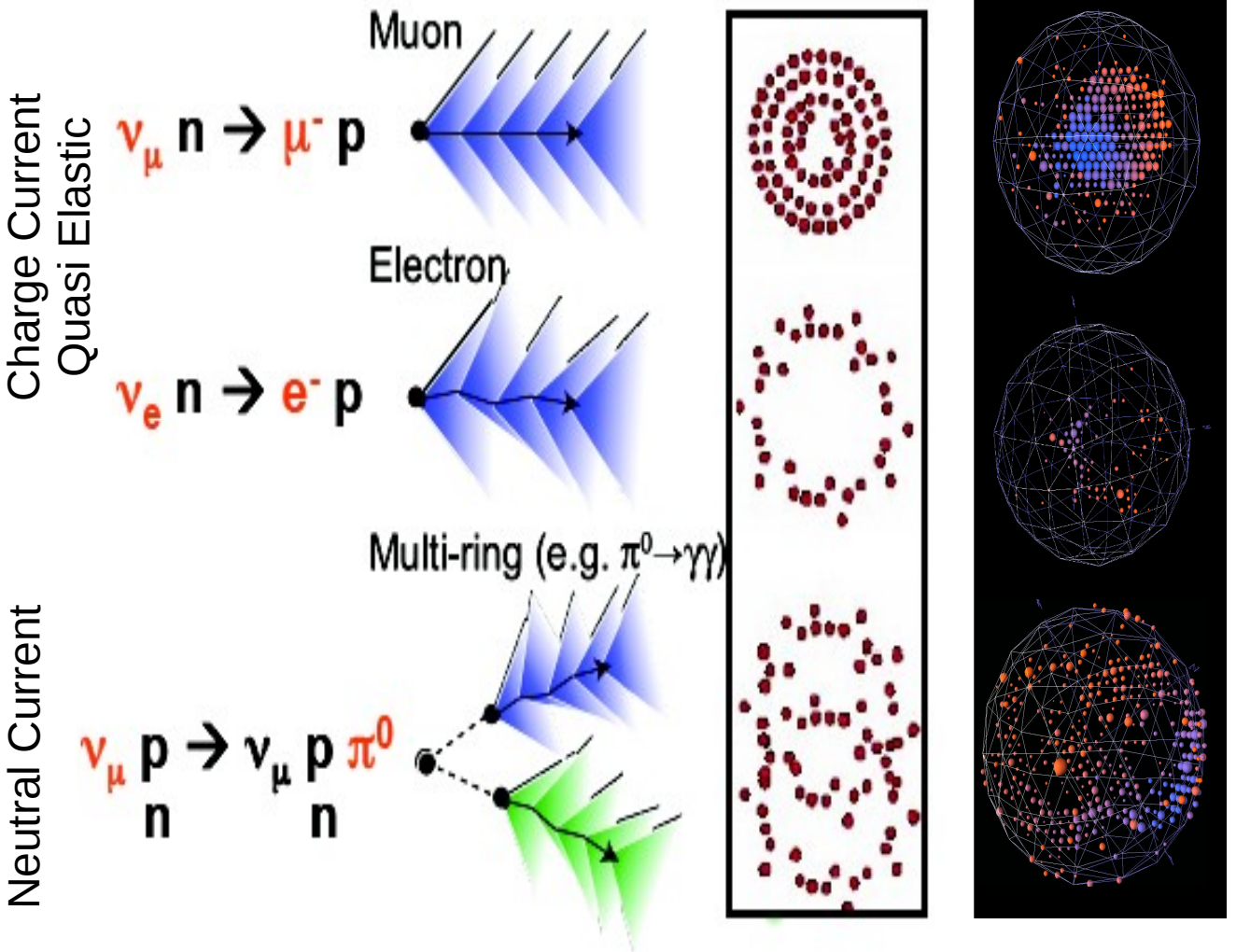


Events in MB

- Identify events using timing and hit topology
- Use primarily Cherenkov light

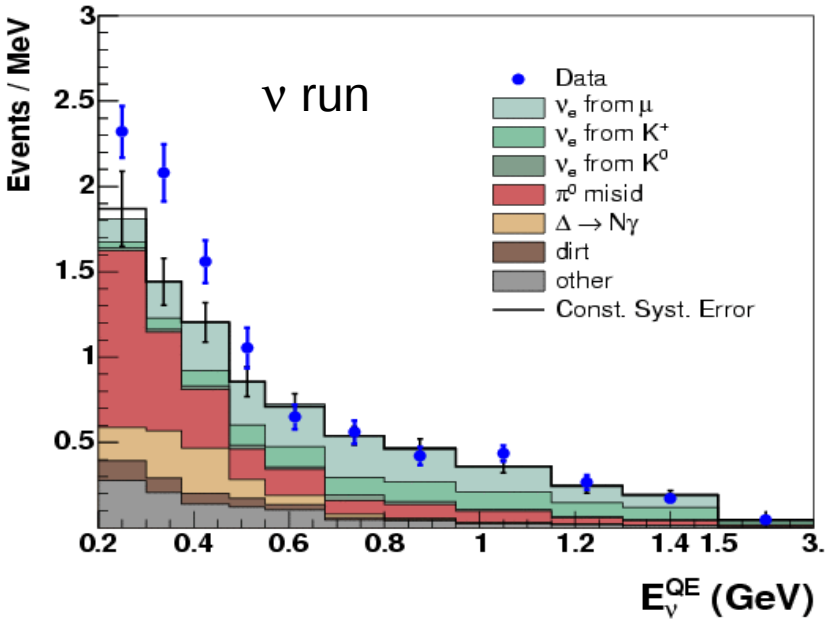
Interactions in MiniBooNE (neutrino mode):

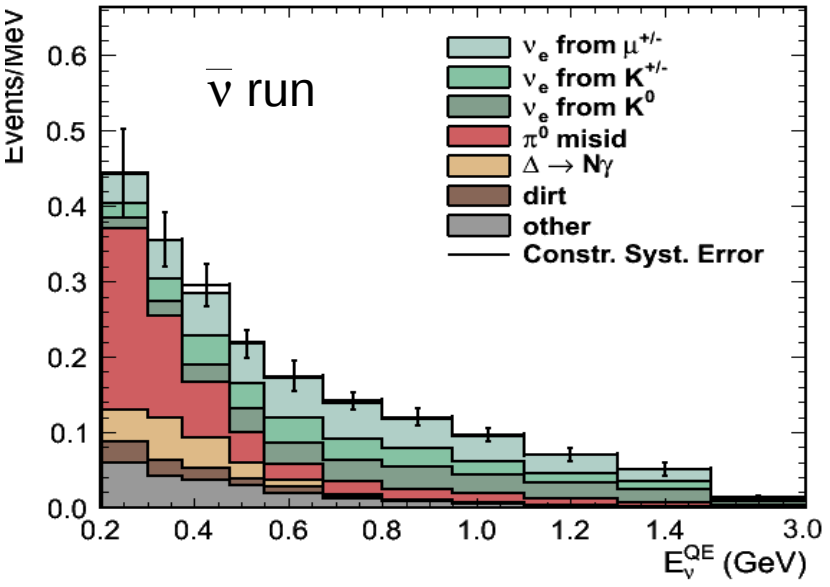




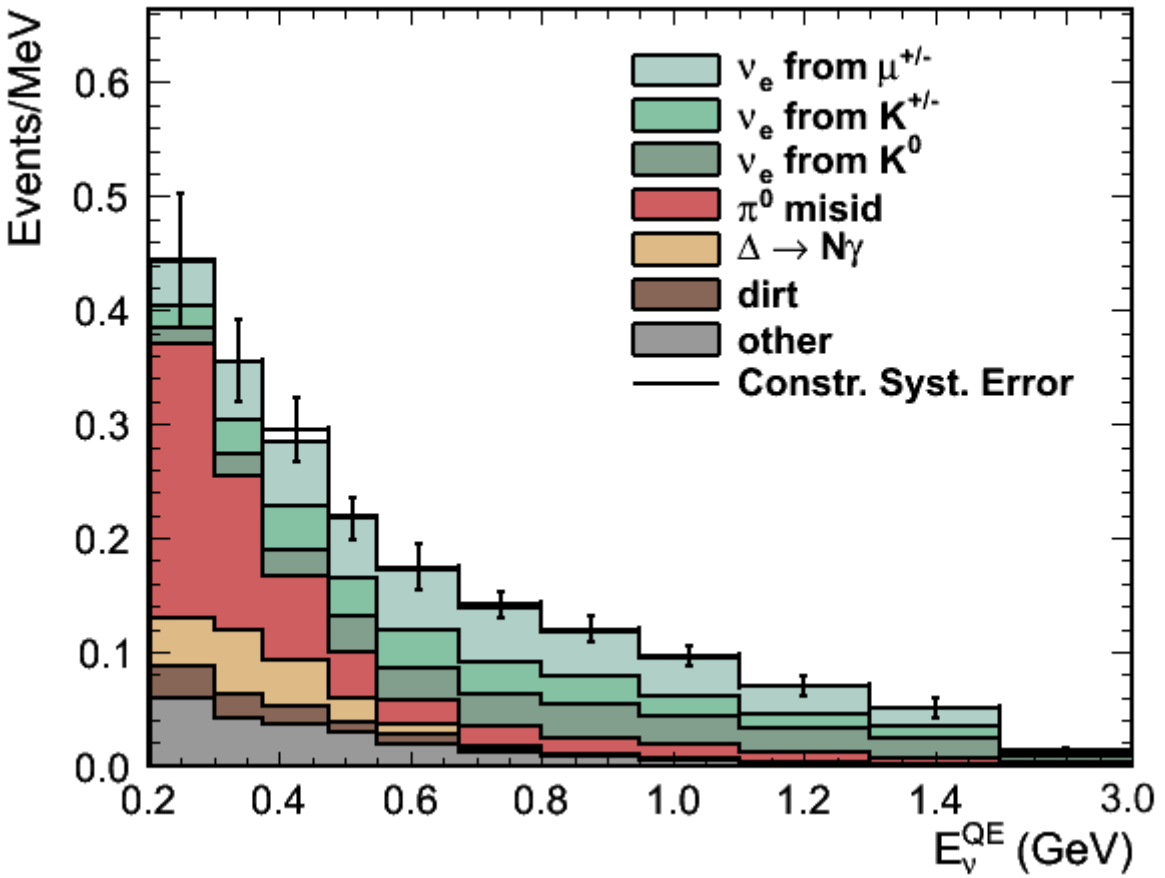
Particle ID

- Same as the one used for ν_e appearance results and also for the first $\bar{\nu}_e$ appearance result
- ID based on ratio of fit likelihoods under different particle hypothesis
- Similar backgrounds in neutrino and anti-neutrino run



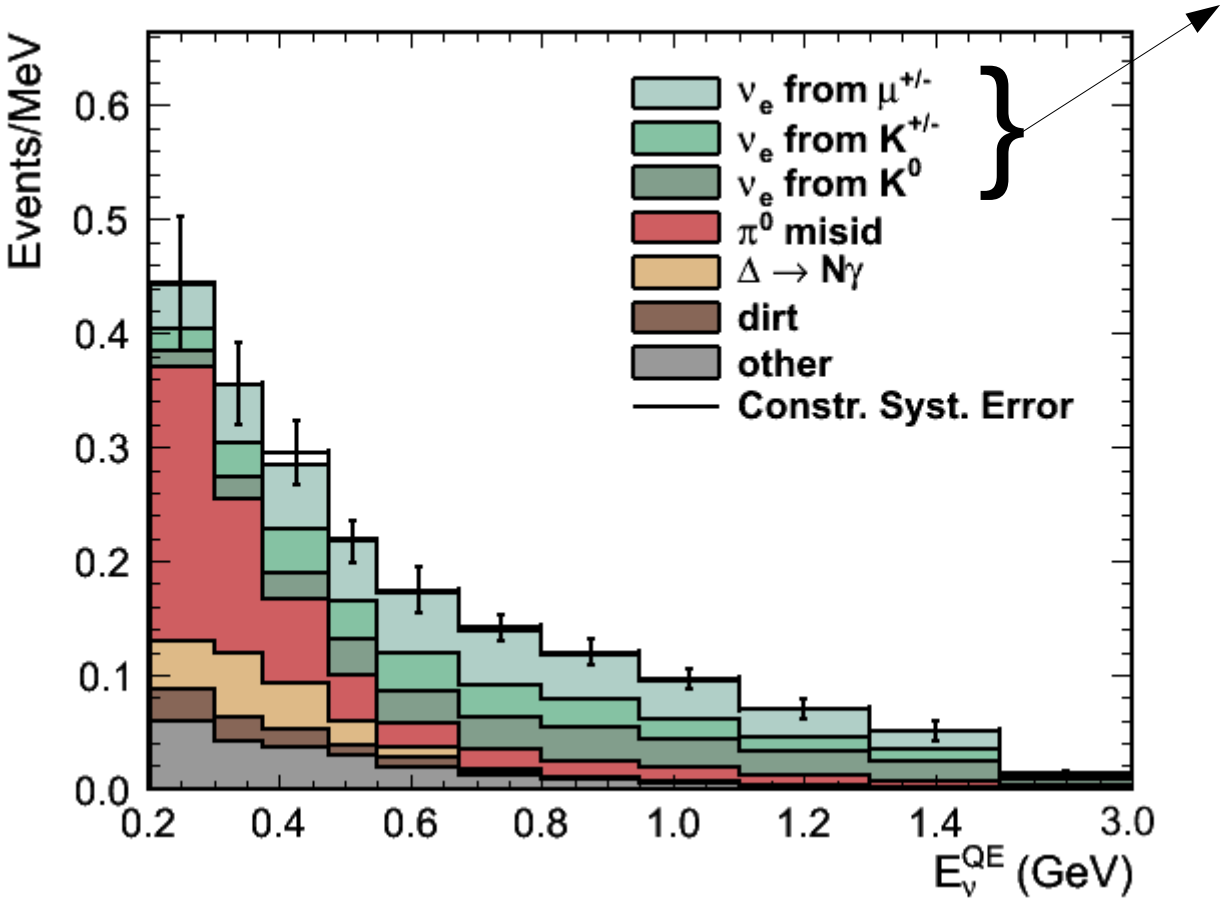


Background prediction

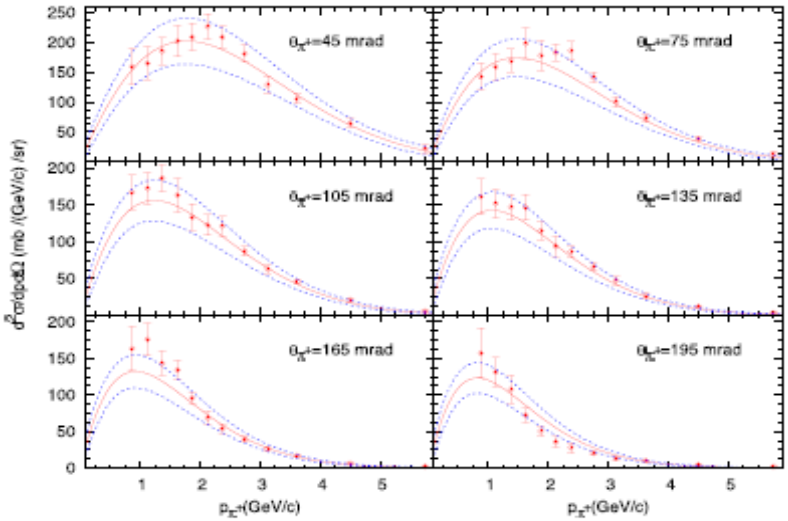


5.66e20 Protons on Target			
	200-475	475-1250	
$\mu^{\pm}$	13.45	31.39	Intrinsic ν_e
$K^{\pm}$	8.15	18.61	
K^0	5.13	21.2	
Other ν_e	1.26	2.05	
NC π^0	41.58	12.57	Mis-ID
$\Delta \rightarrow N\gamma$	12.39	3.37	
dirt	6.16	2.63	
ν_μ CCQE	4.3	2.04	
Other ν_μ	7.03	4.22	
Total	99.45	98.08	

Background prediction



- Intrinsic nue
  - External measurements
    - HARP p+Be for $\pi^{\pm}$

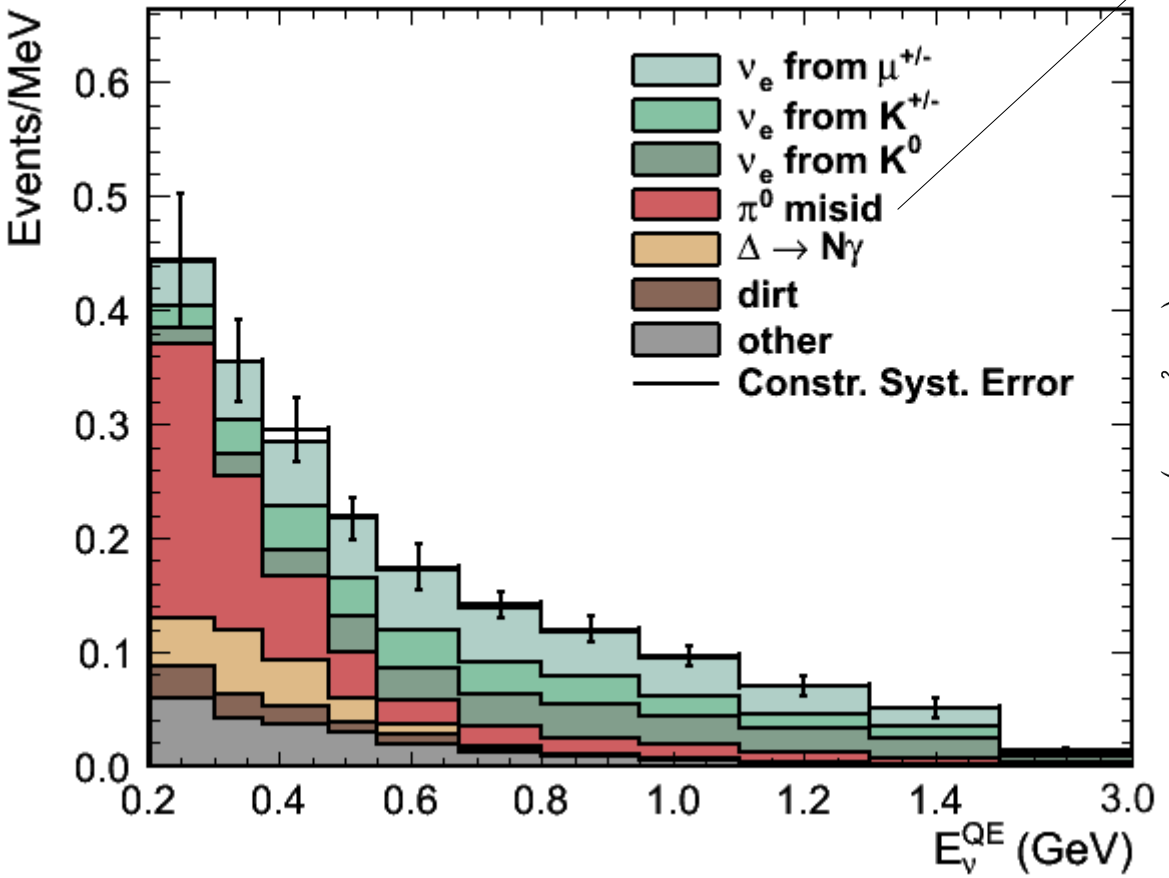


    - Sanford-Wang fits to world K^+/K^0 data

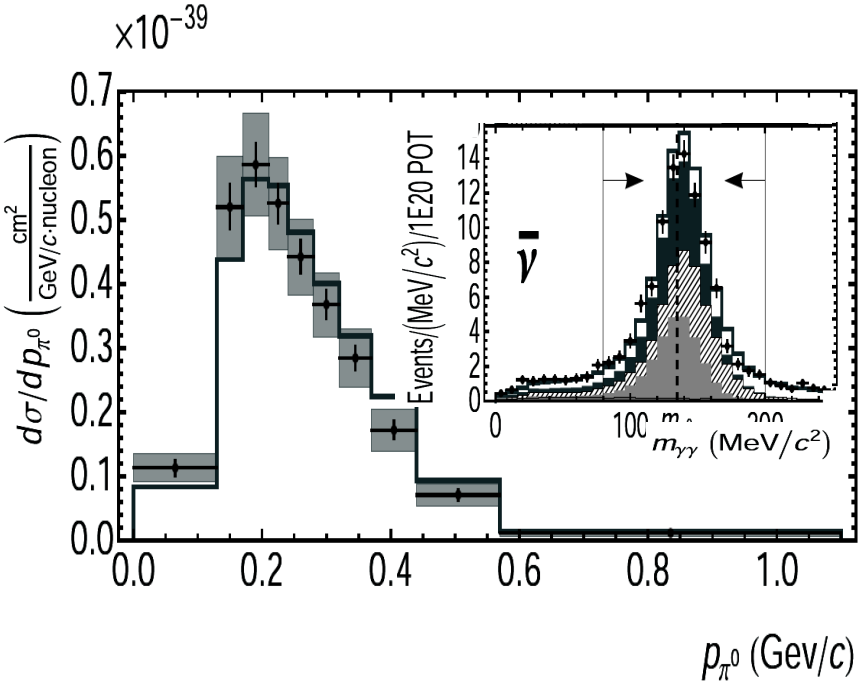
Phys. Rev. D79, 072002 (2009)

- MiniBooNE data constrained

Background prediction



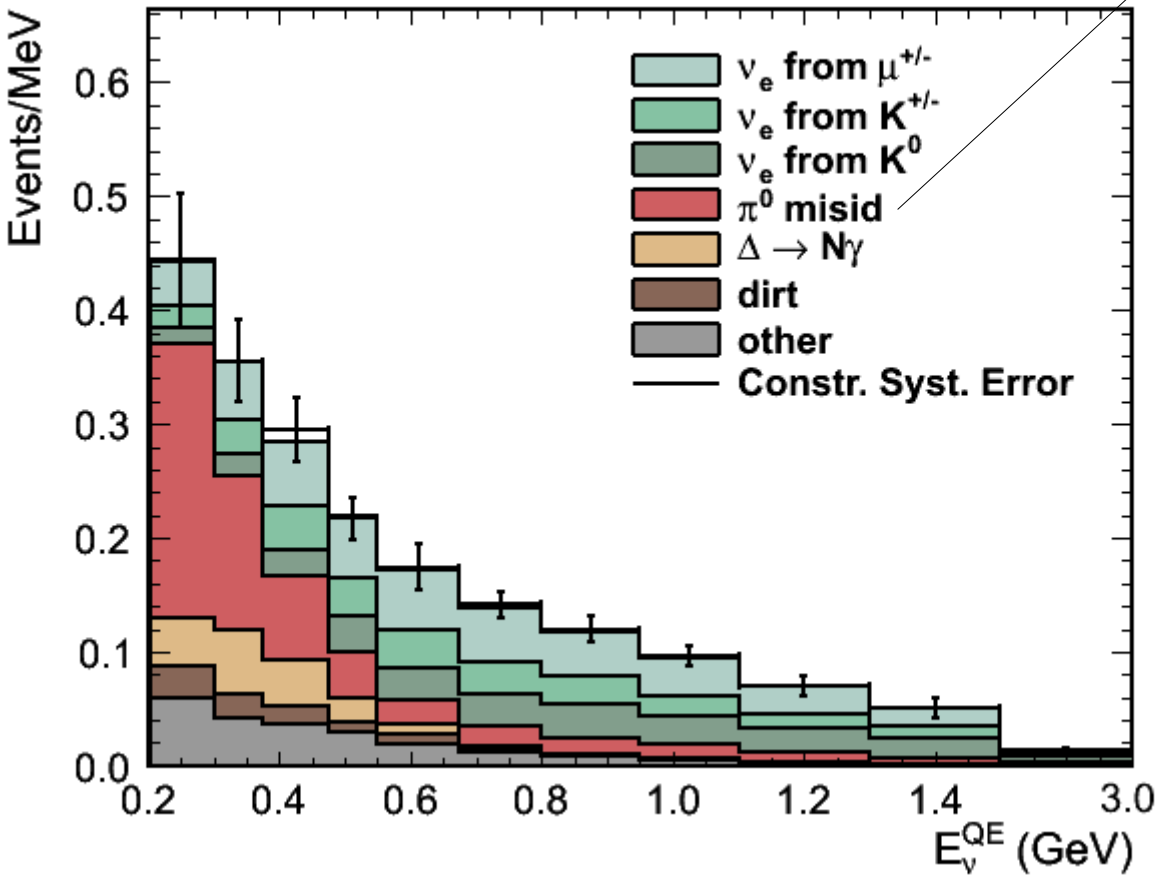
- NC π^0
  - MiniBooNE measurement



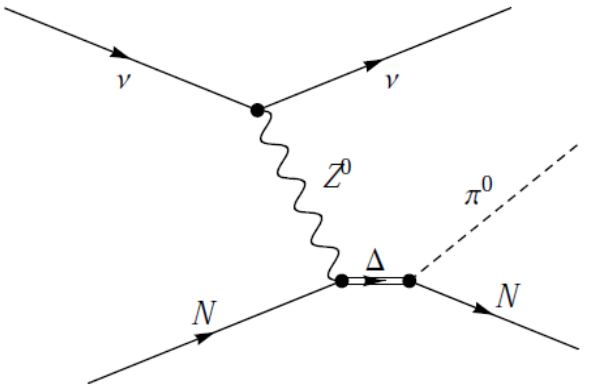
Phys. Rev. D81, 013005 (2010)

Background prediction

- NC π^0

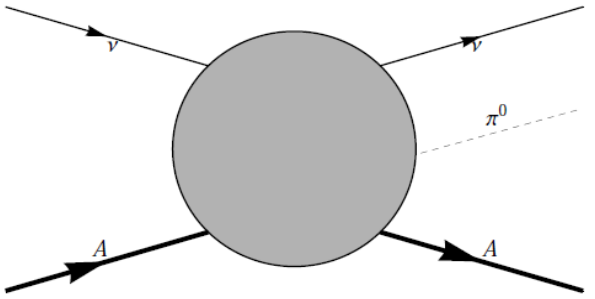


Resonant (~80%)

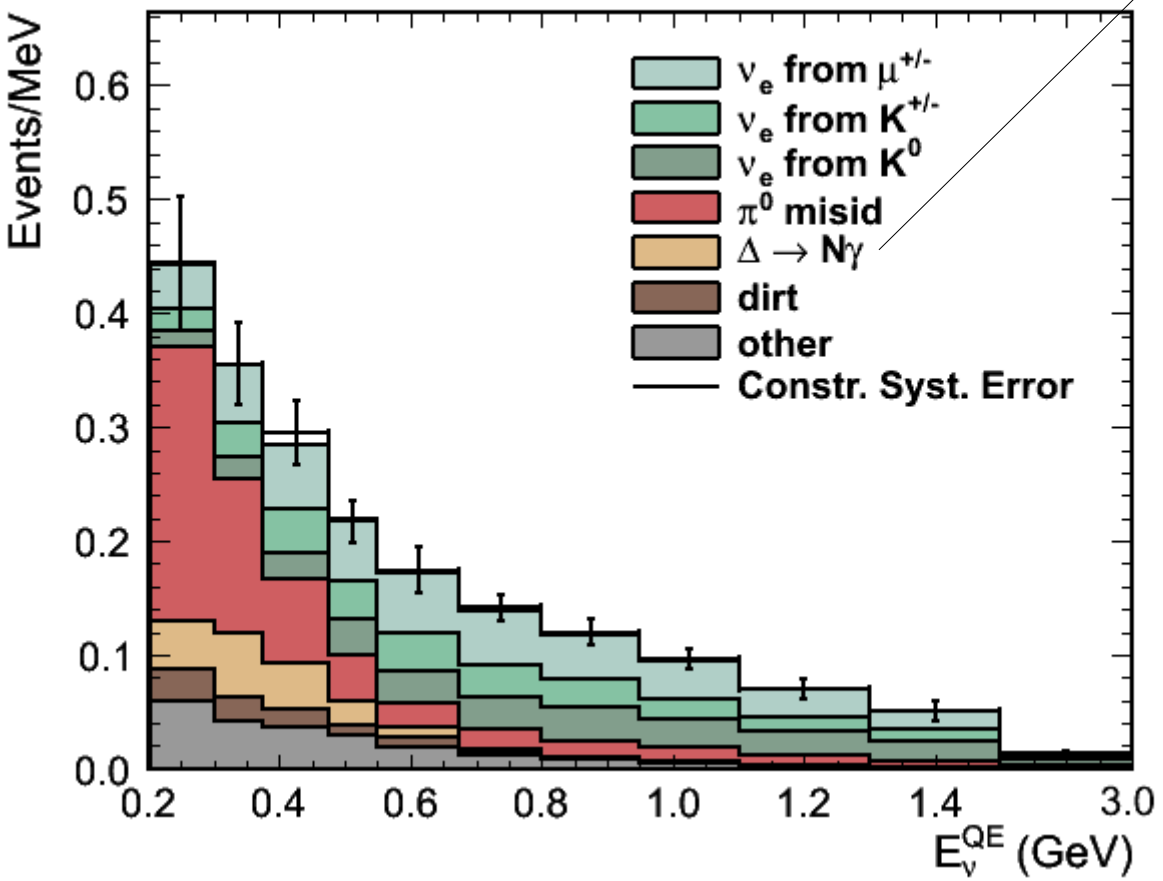


+

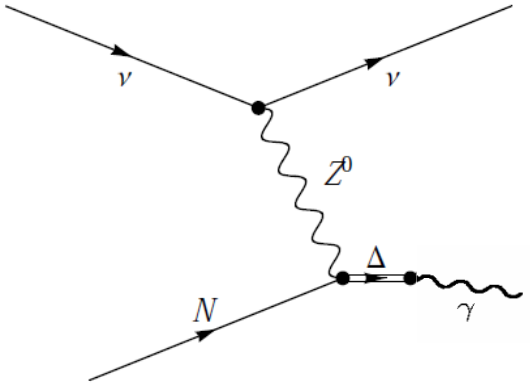
Coherent (~20%)



Background prediction

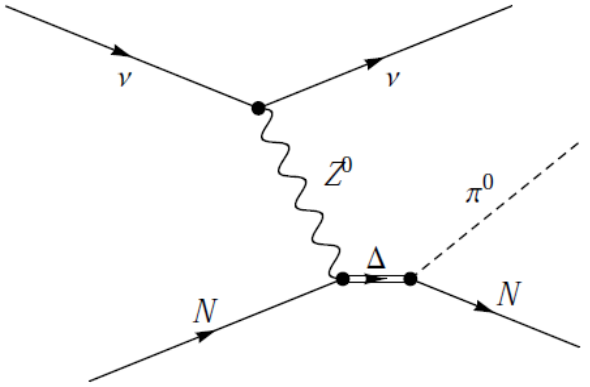


- Radiative delta



- Use NC π^0 measurement to constrain

Resonant π^0



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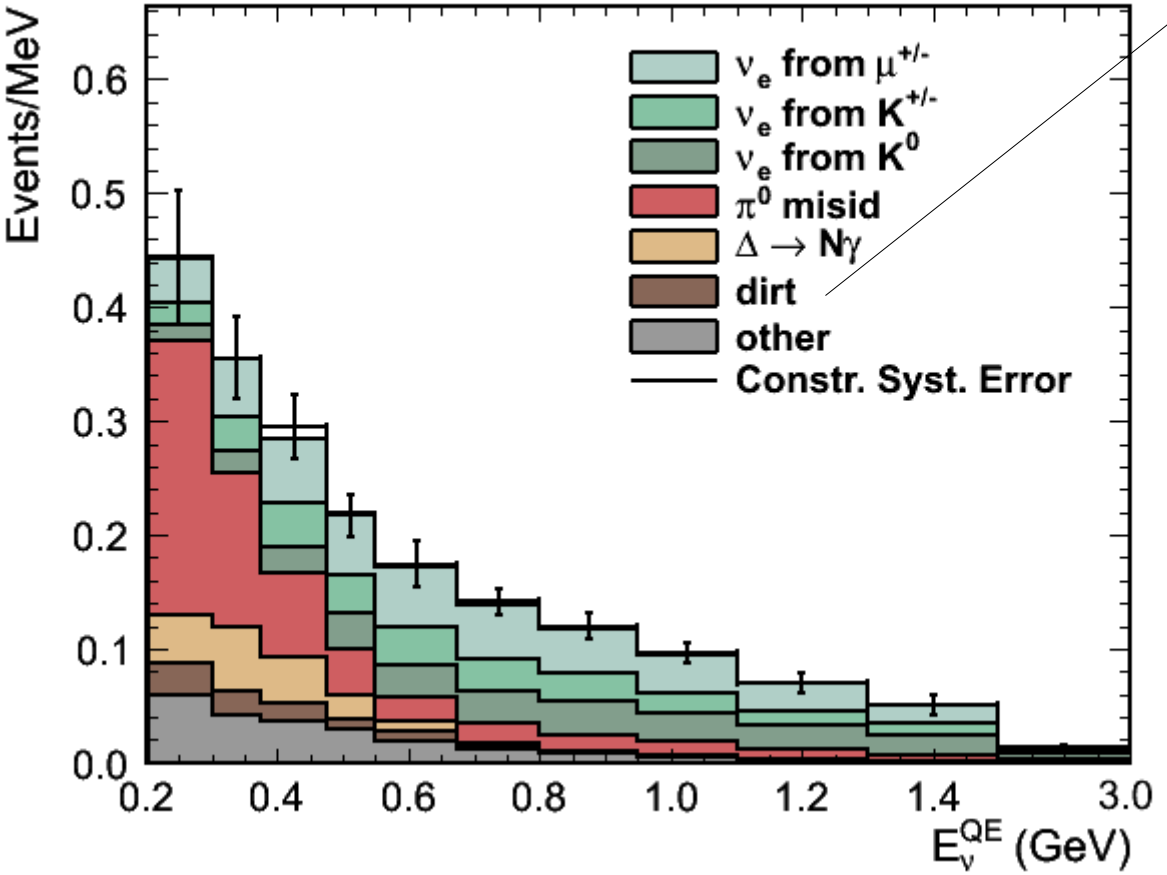
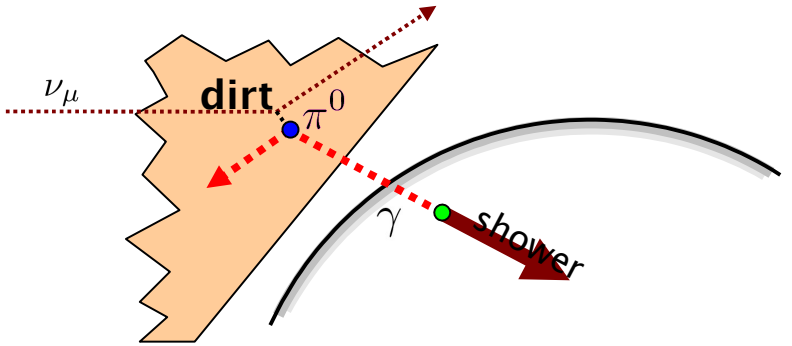


- Dirt:



- Events at high R pointing toward center of detector
- MiniBooNE measurement

ν_e Background Uncertainties

Uncertainty (%)	200-475MeV	475-1100MeV
π^+	0.4	0.9
π^-	3	2.3
K^+	2.2	4.7
K^-	0.5	1.2
K^0	1.7	5.4
Target and beam models	1.7	3
Cross sections	6.5	13
NC pi0 yield	1.5	1.3
Hadronic interactions	0.4	0.2
Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.4%	16.0%

- Unconstrained ν_e background uncertainties
- Propagate input uncertainties from either MiniBooNE measurement or external data

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- Uncertainty determined by varying underlying cross section model parameters (M_A, Pauli blocking, …)
- Many of these parameters measured in MiniBooNE

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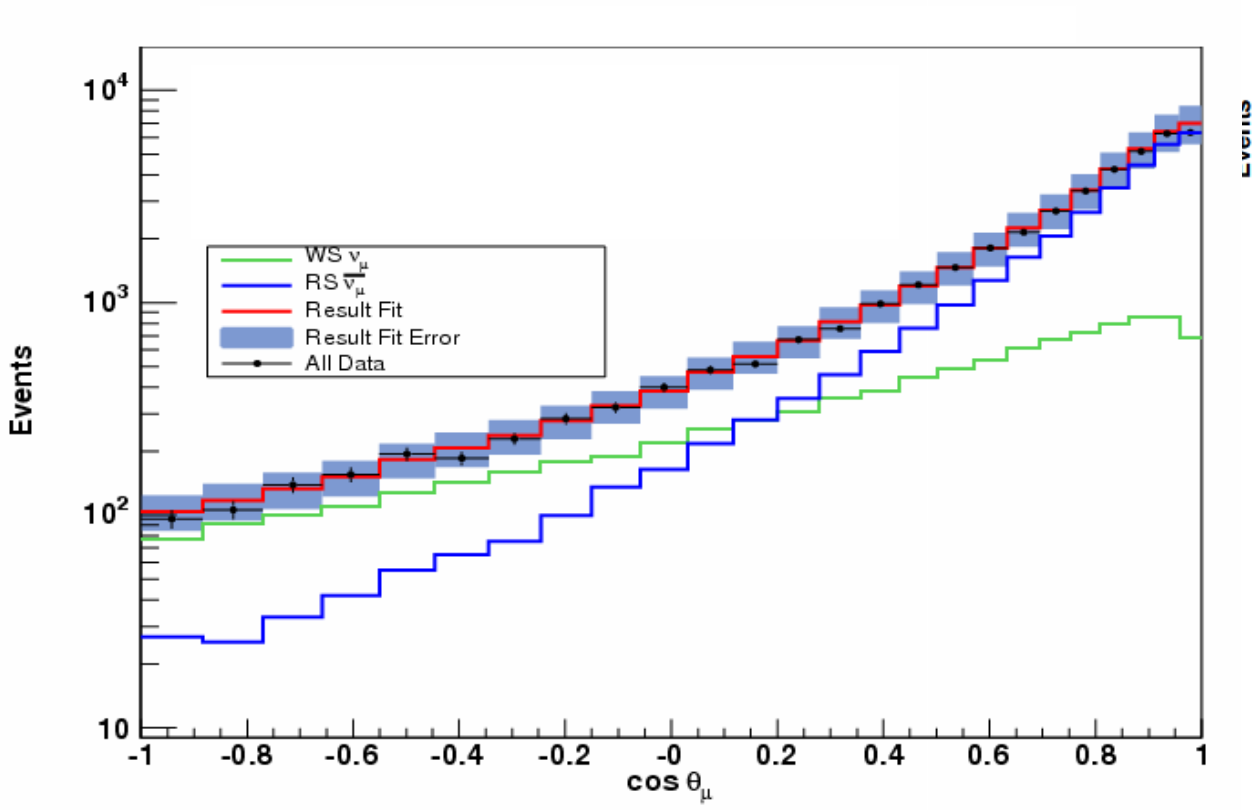
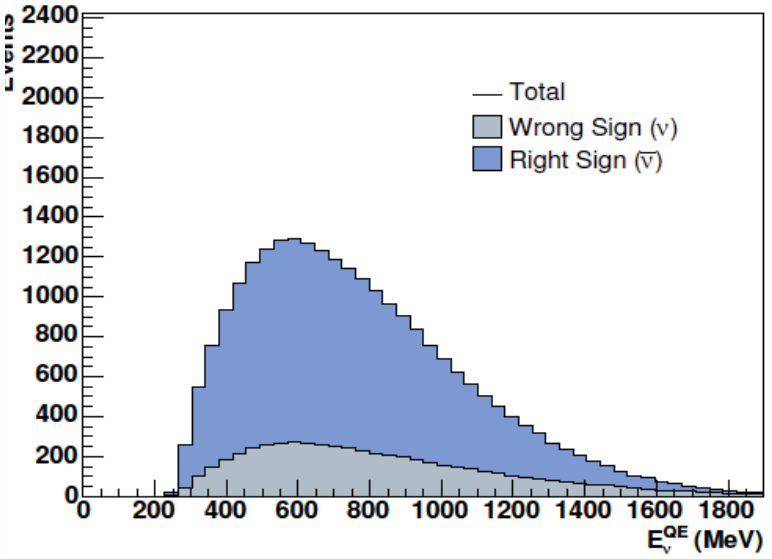
- Uncertainty in light creation, propagation and detection in the detector

Signal prediction

- Assuming only right sign oscillates ($\bar{\nu}_\mu$)
- Need to know wrong sign vs right sign
- $\bar{\nu}_\mu$ CCQE gives more forward peaked muon





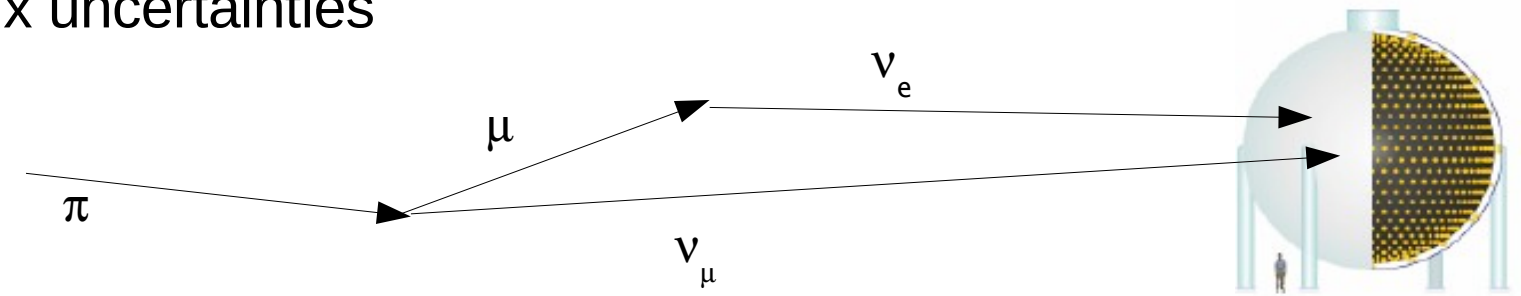
Paper in progress

Oscillation Fit Method

- Maximum likelihood fit:

$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

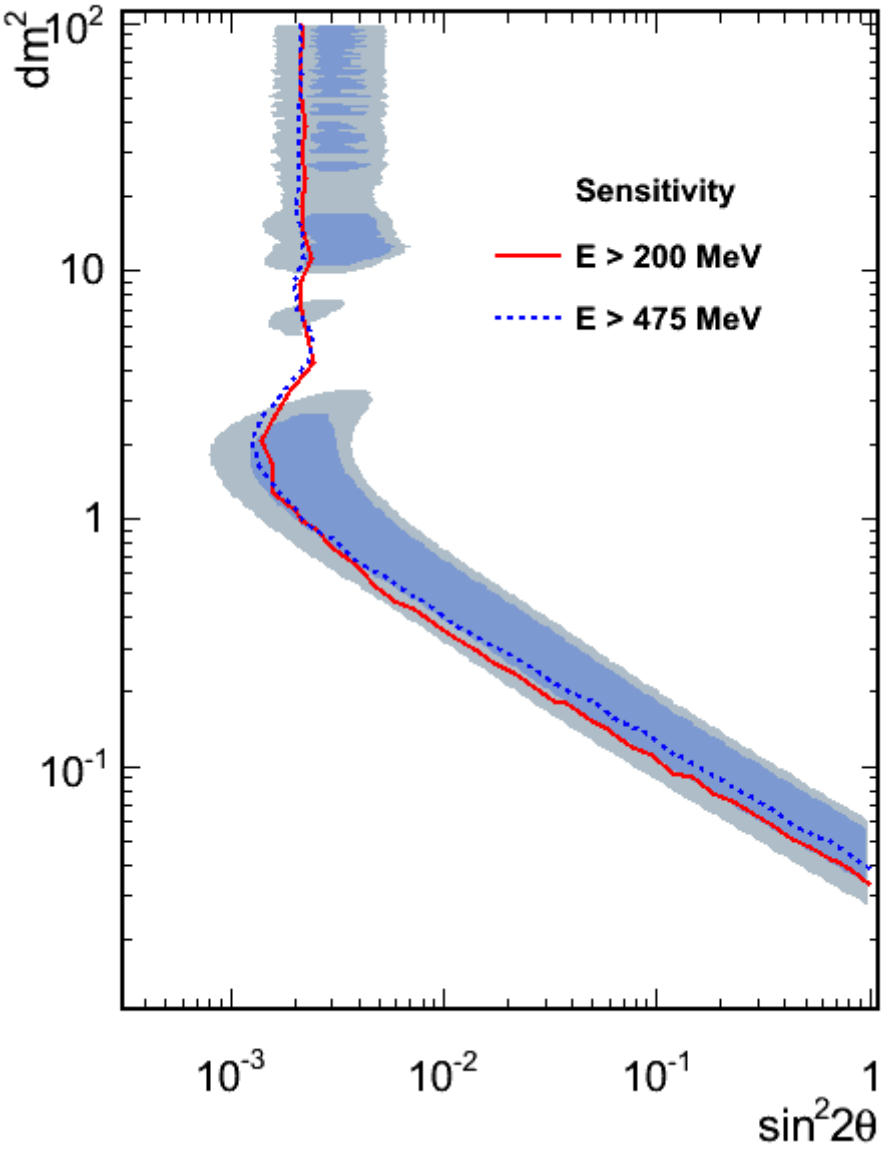
- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties



  - Cross section uncertainties

Sensitivity

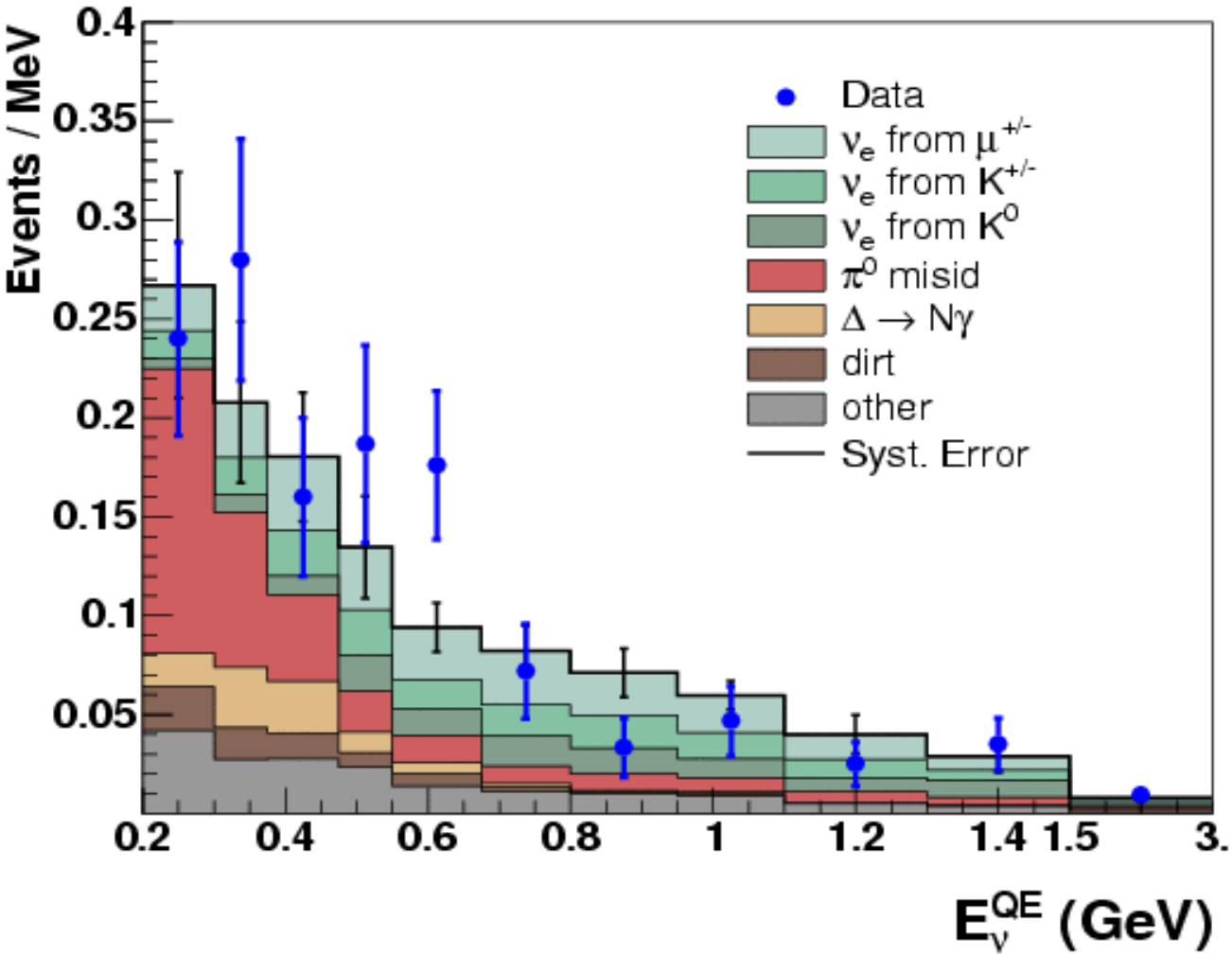
- MiniBooNE uses E>475MeV for oscillation fits
- Energy region where expect LSND type signal
- E<475:
  - Large backgrounds
  - Big systematics
  - Not sensitive to LSND oscillation signal



Results

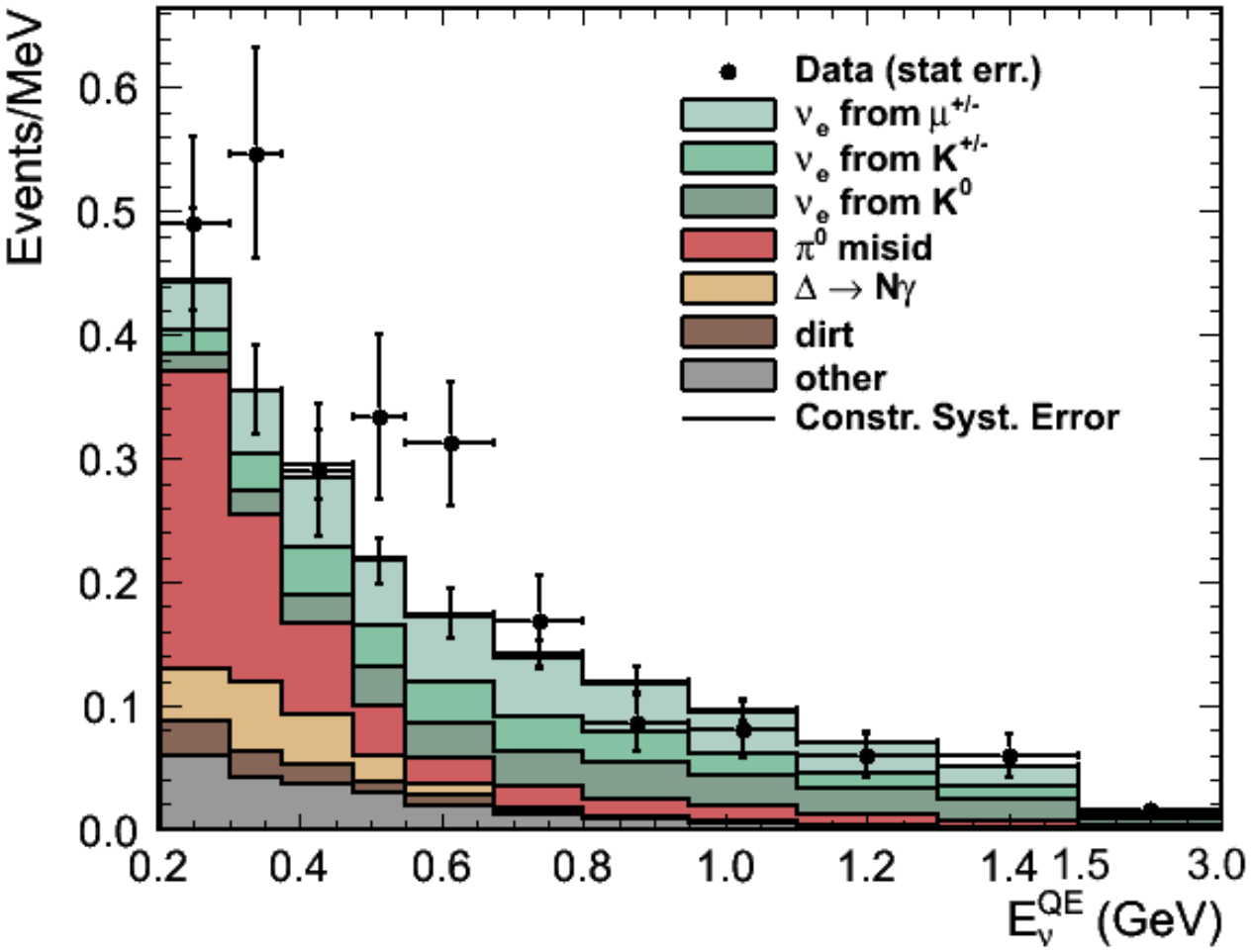
First nuebar appearance result

- W&C December 2008
- Using 3.4e20 POT

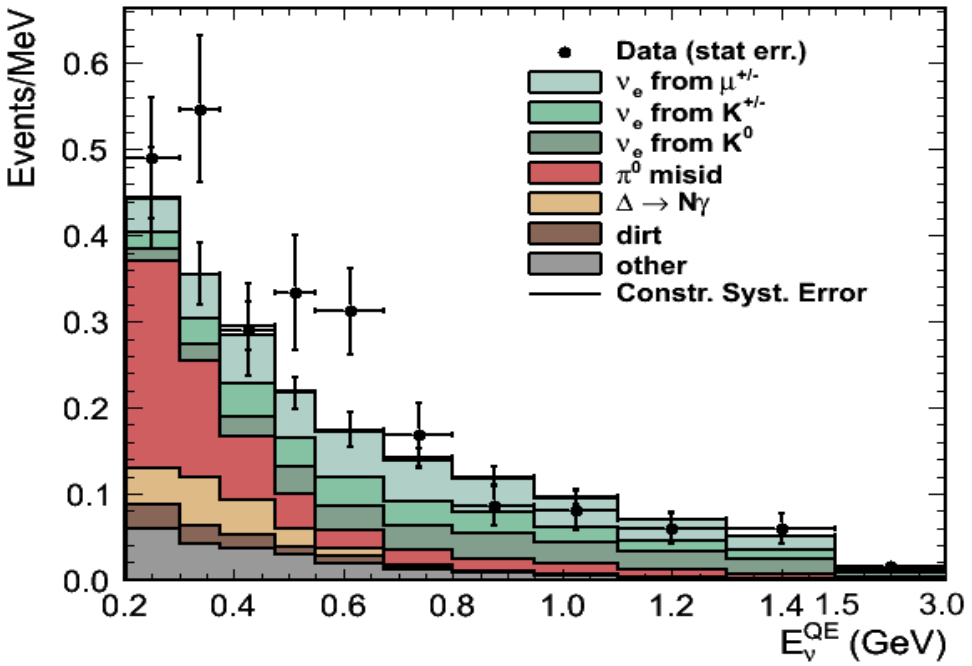


New Anti-neutrino data

- 5.66e20 POT
- ~70% more data



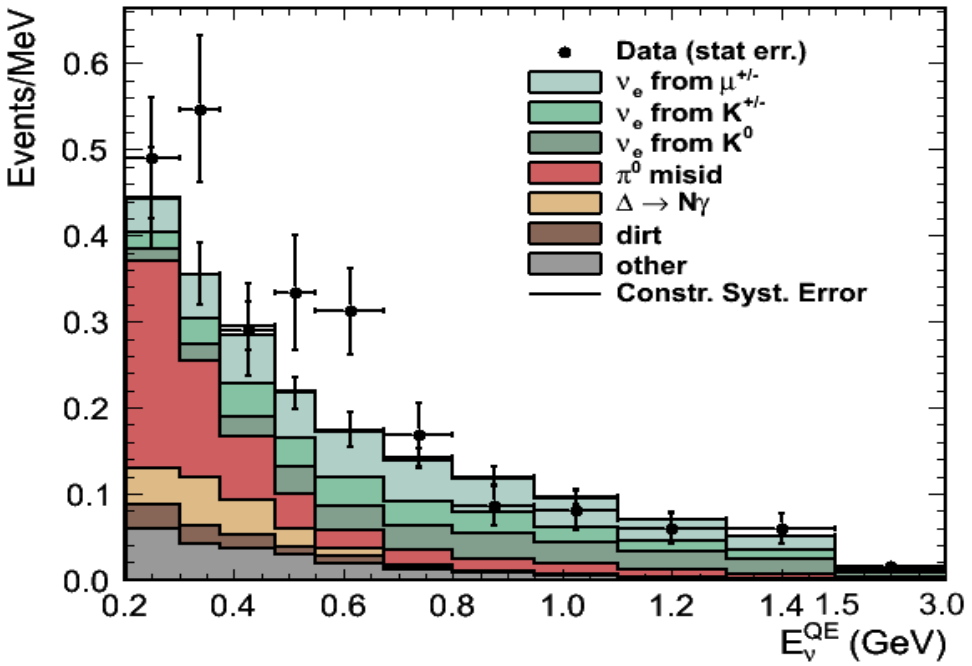
New Anti neutrino data



	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from ν low E excess	11.6	0
LSND+Low E	19.2	22

- Excess of events in both 200-475MeV and 475-1250MeV region
- Assuming only neutrinos produce low energy excess expect 11.6 events in 200-475MeV region

New Anti neutrino data



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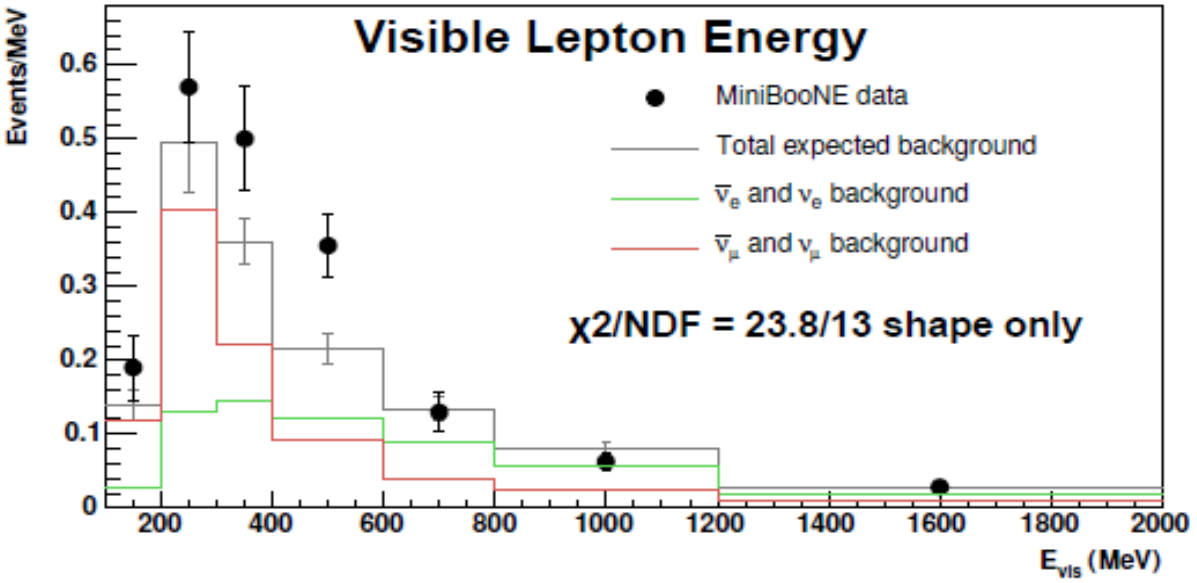
LSND Best Fit	7.6	22
Expectation from ν low E excess	11.6	0
LSND+Low E	19.2	22

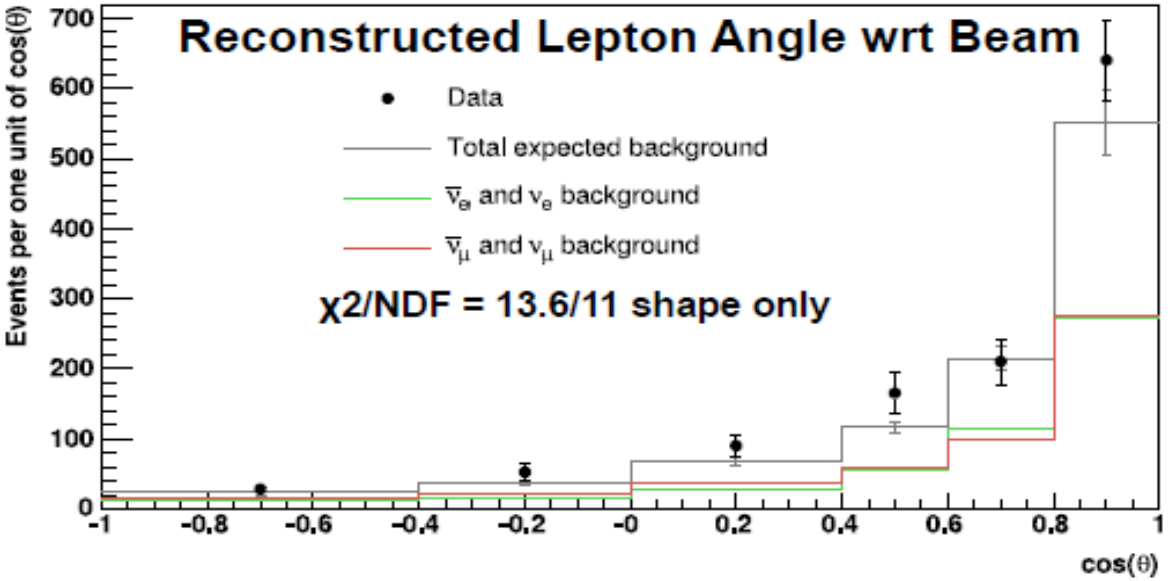
- Excess of events in both 200-475MeV and 475-1250MeV region
- If low E excess is due to Standard Model NC gamma-ray mechanism, eg Axial Anomaly, expect ~67 excess events in 200-475MeV

  (scaling excess by the ratio of total flux in ν and $\bar{\nu}$ mode)

Other kinematic distributions

- 5.66e20
- $\bar{\nu}_e$ sample



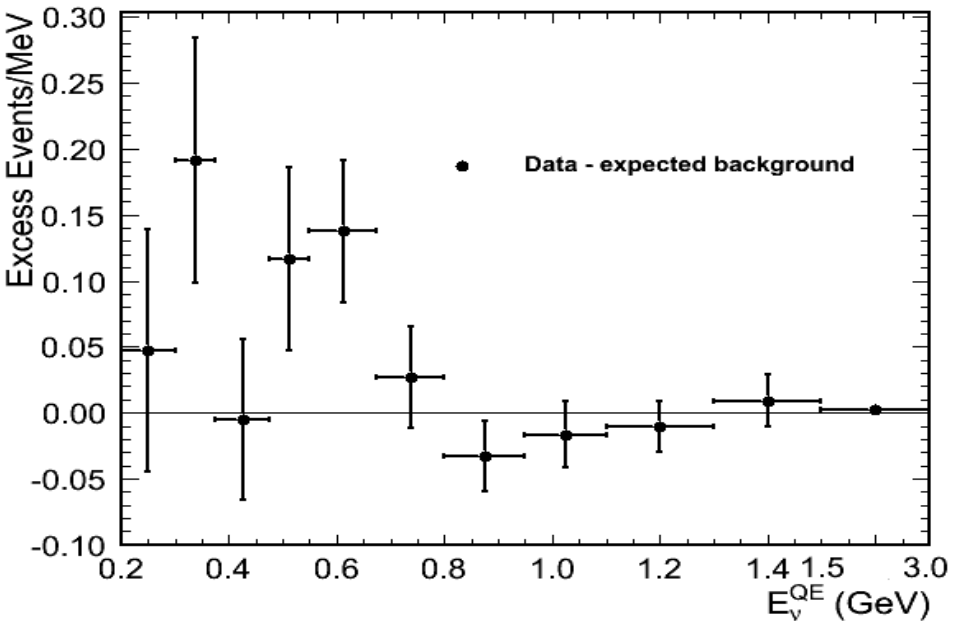


Null probability

- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

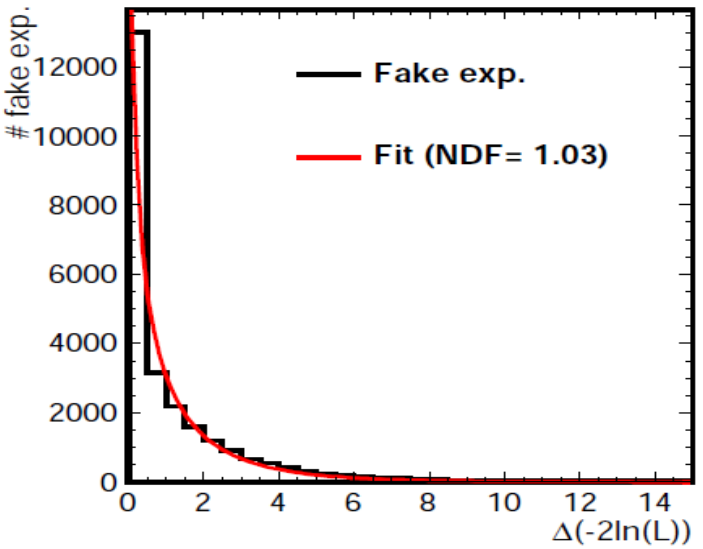
	chi2/NDF	probability
E>475MeV	26.8/14.9	3.0%
* E>200MeV	33.2/18.0	1.6%

* No assumption about low E excess made



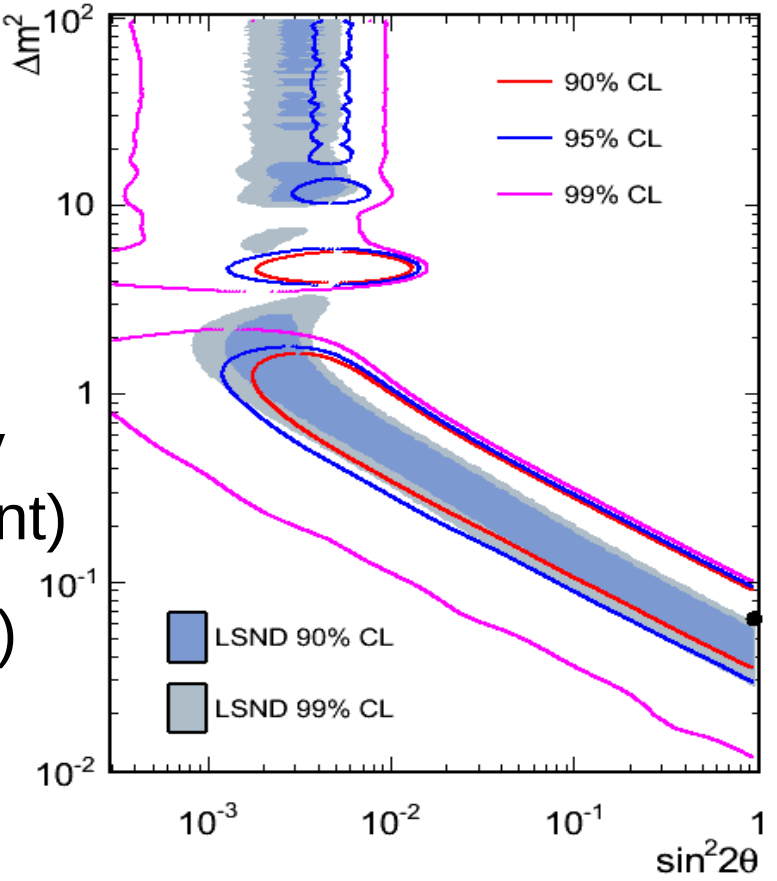
Drawing contours

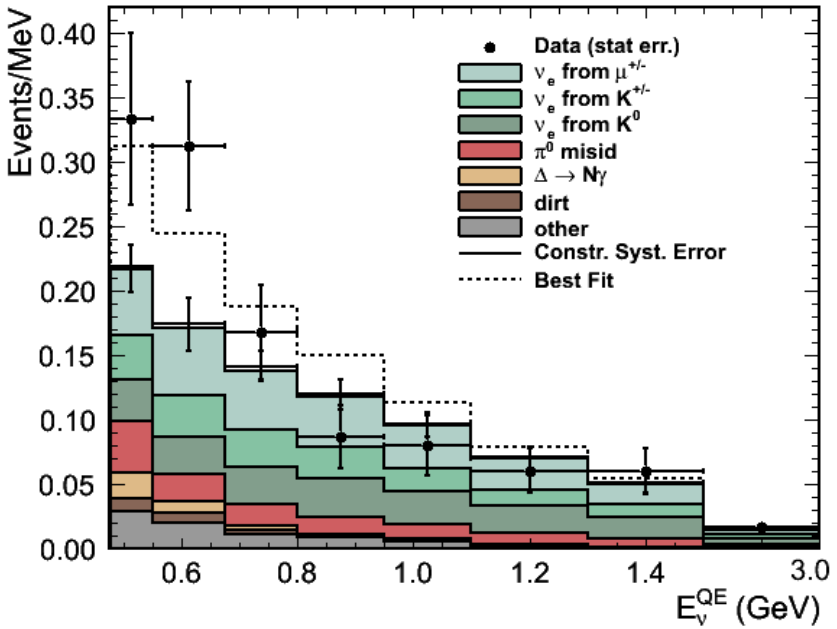
- Frequentist approach
- Fake data experiments on grid of ($\sin^2 2\theta$, Δm^2) points
- At each point find the cut on likelihood ratio for X% confidence level such that X% of experiments below cut
- Fitting two parameters, so naively expect χ^2 distribution with 2 degrees of freedom, in reality at null it looks more like 1 degree of freedom

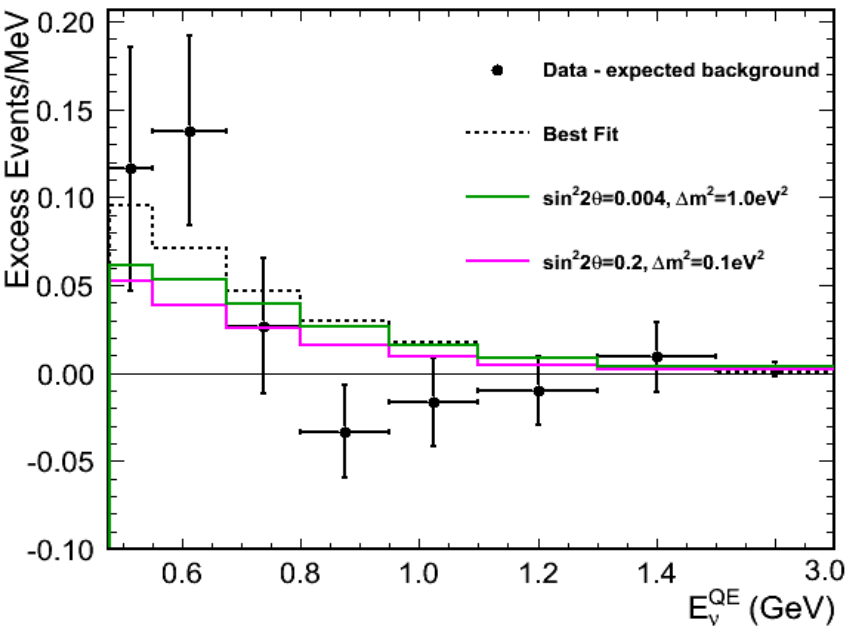


Fit E>475

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.9584, 0.064 eV^2)
  χ^2/NDF = 16.4/12.6
  p=20.5%

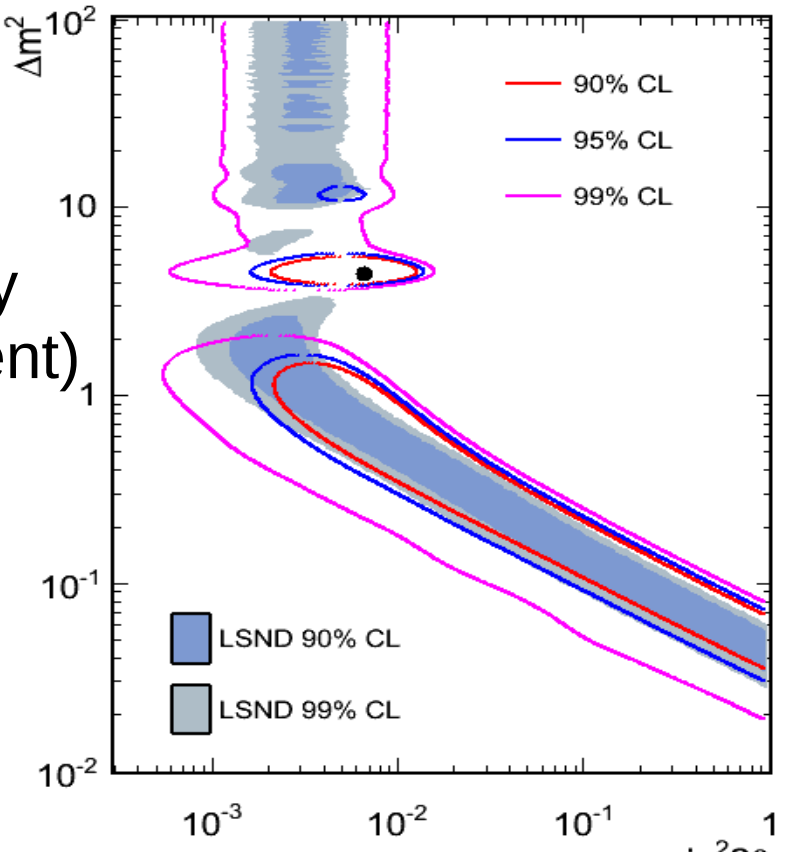


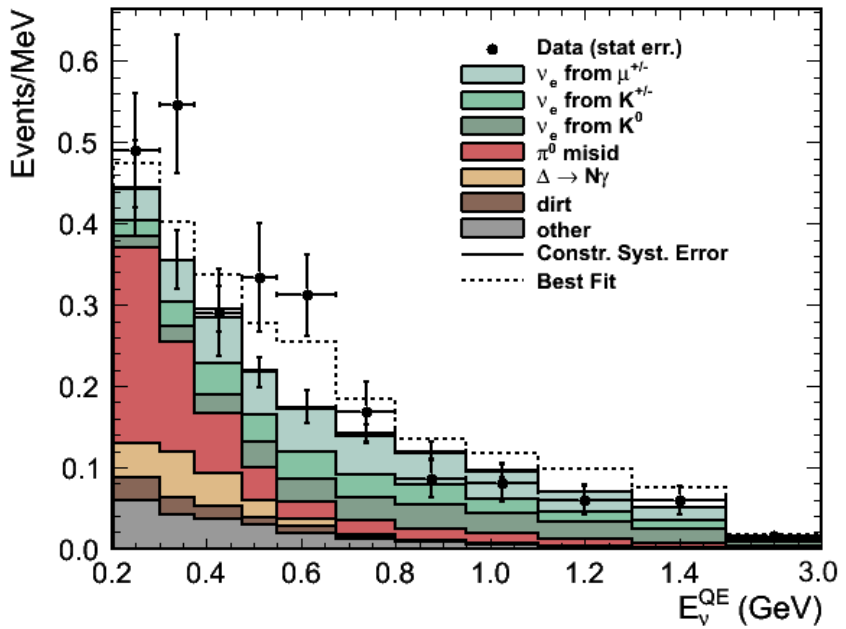


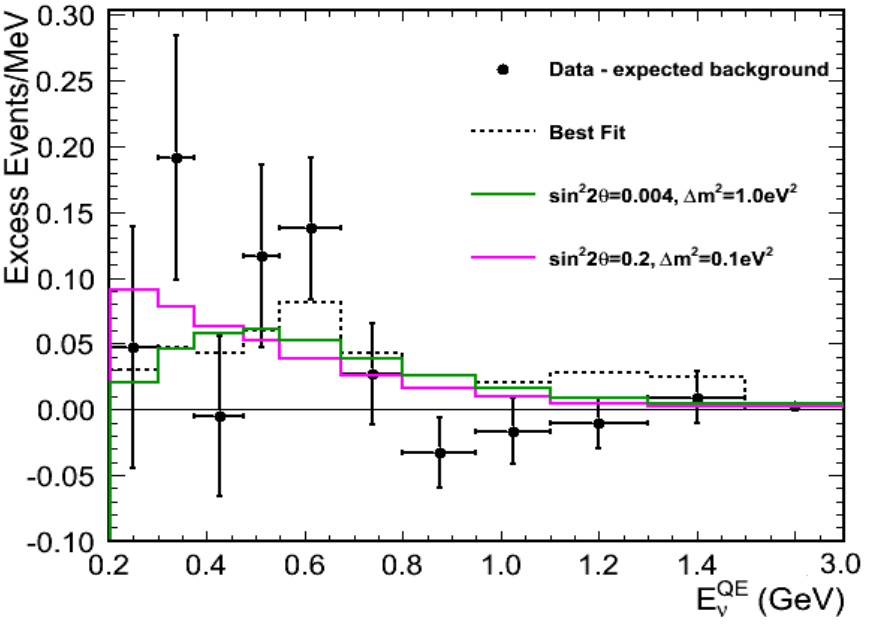


E>200MeV

- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.0066, 4.42 eV^2)
  χ^2/NDF = 20.4/15.3
  p=17.1%



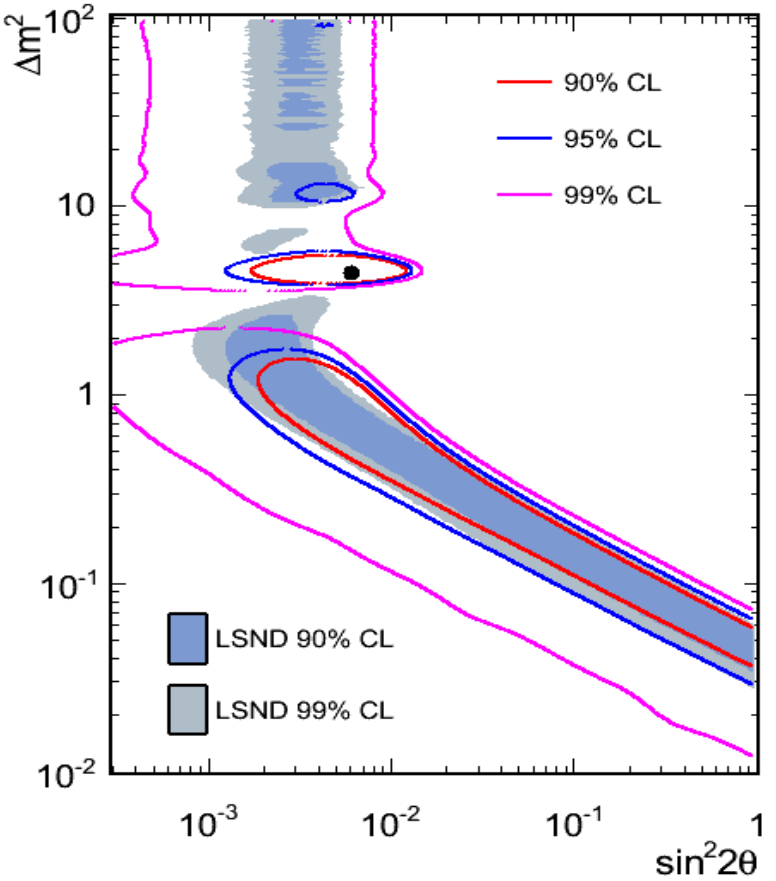


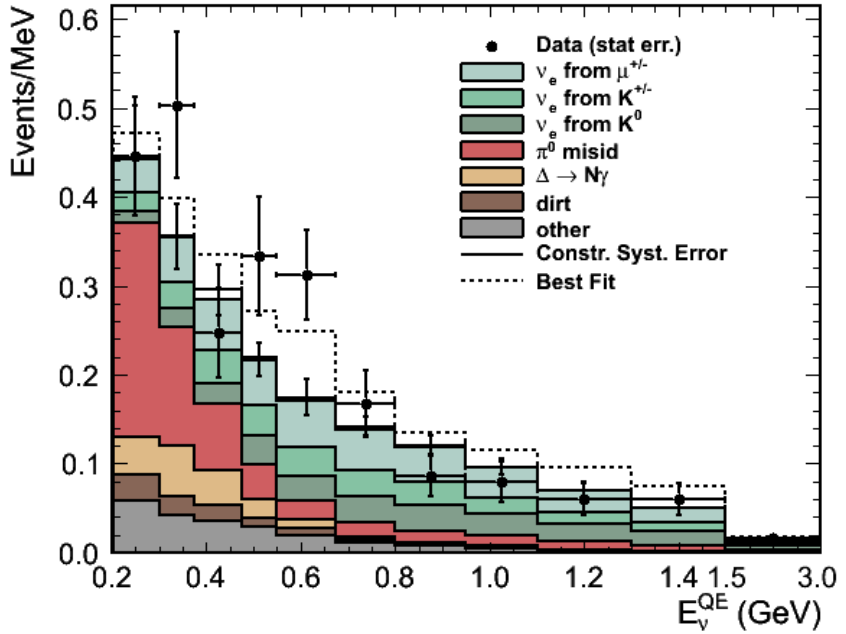


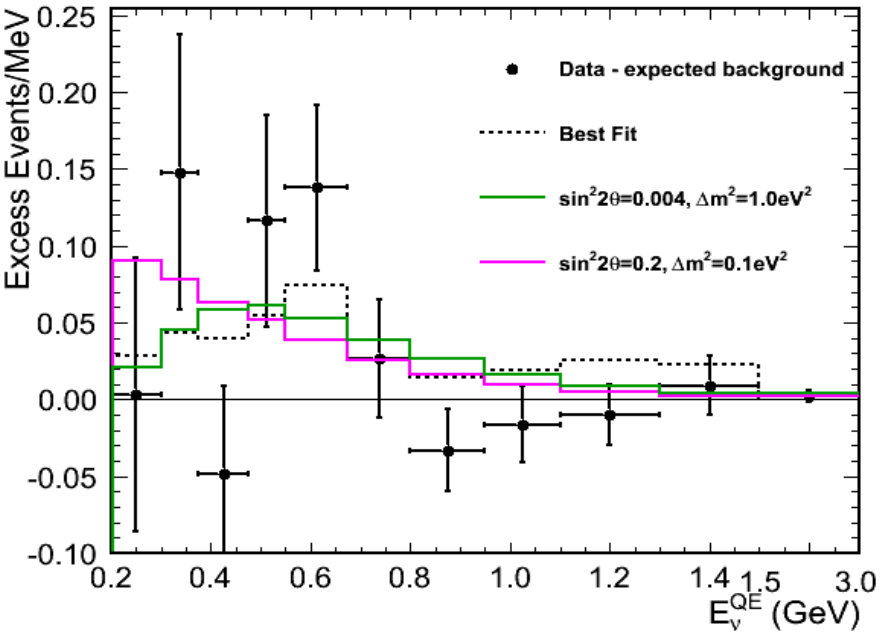
E>200MeV

- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- E<475MeV:
  - Large background
  - Not relevant for LSND type osc.
  - Big systematics
- Null χ^2=32.8; p=1.7%

Best fit ($\sin^2 2\theta$, Δm^2) = (0.0061, 4.42 eV^2)
χ^2/NDF = 21.6/15.3; p=13.7%



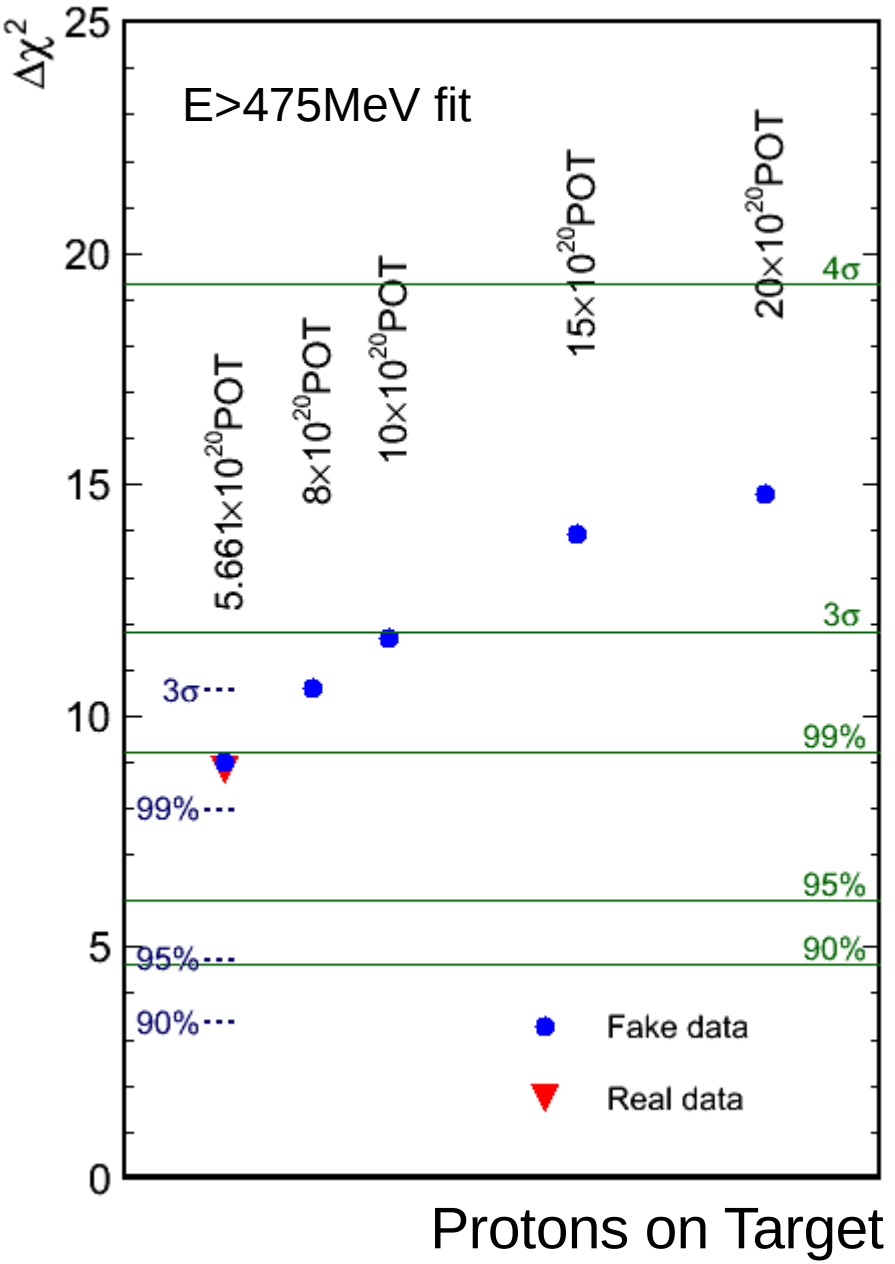




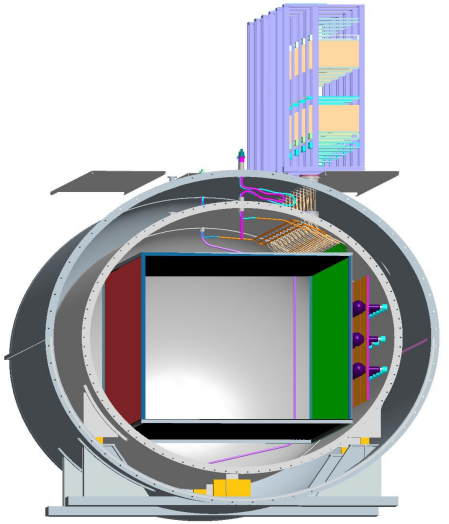
Future outlook

Future sensitivity

- MiniBooNE approved for a total of 1e21 POT
- Potential exclusion of null point assuming best fit signal
- Combined analysis of ν_e and $\bar{\nu}_e$



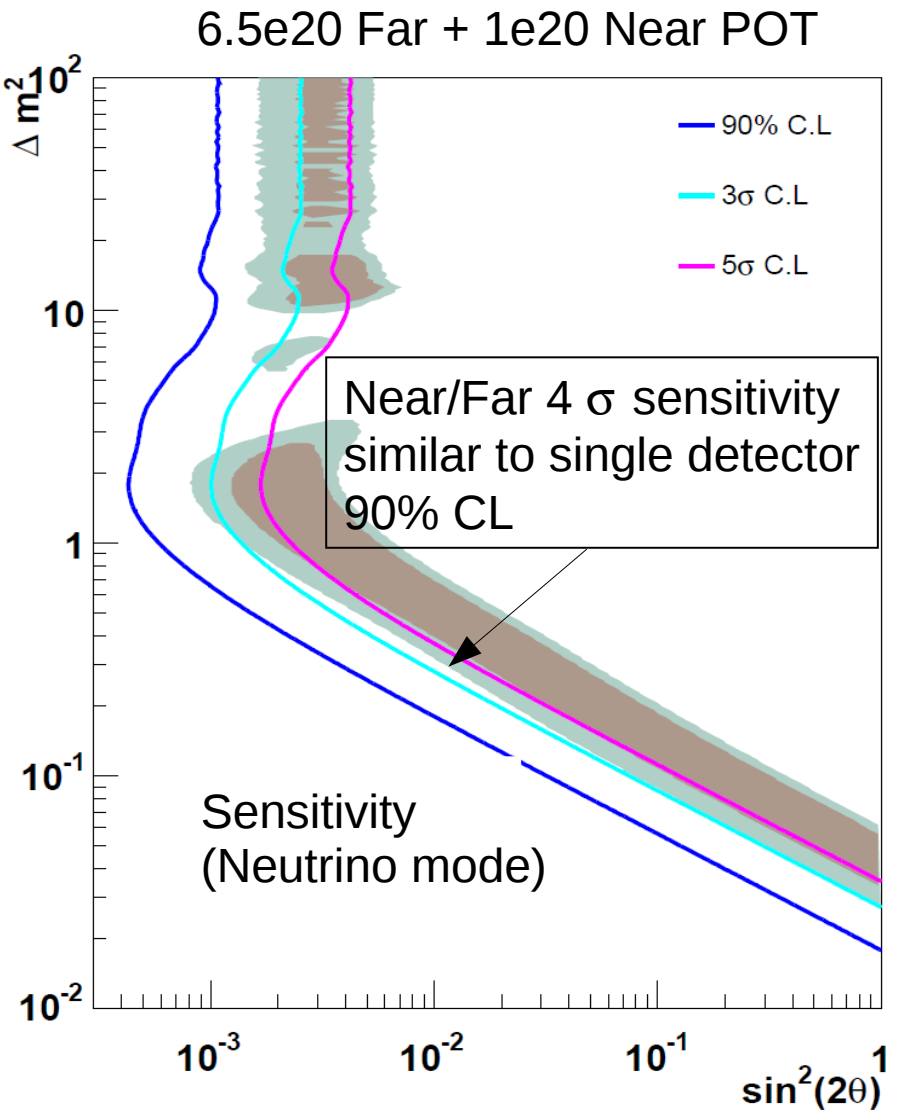
Future experiments



- Microboone
  - CD1 approved
  - Address low energy excess
- Few ideas under consideration:
  - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
  - Redoing a stopped pion source at ORNL (OscSNS - http://physics.calumet.purdue.edu/~oscsns/) or Project X
  - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)

BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Present neutrino low energy excess is 6 sigma statistical; 3 sigma when include systematics
- Study L/E dependence
- Gain statistics quickly, already have far detector data

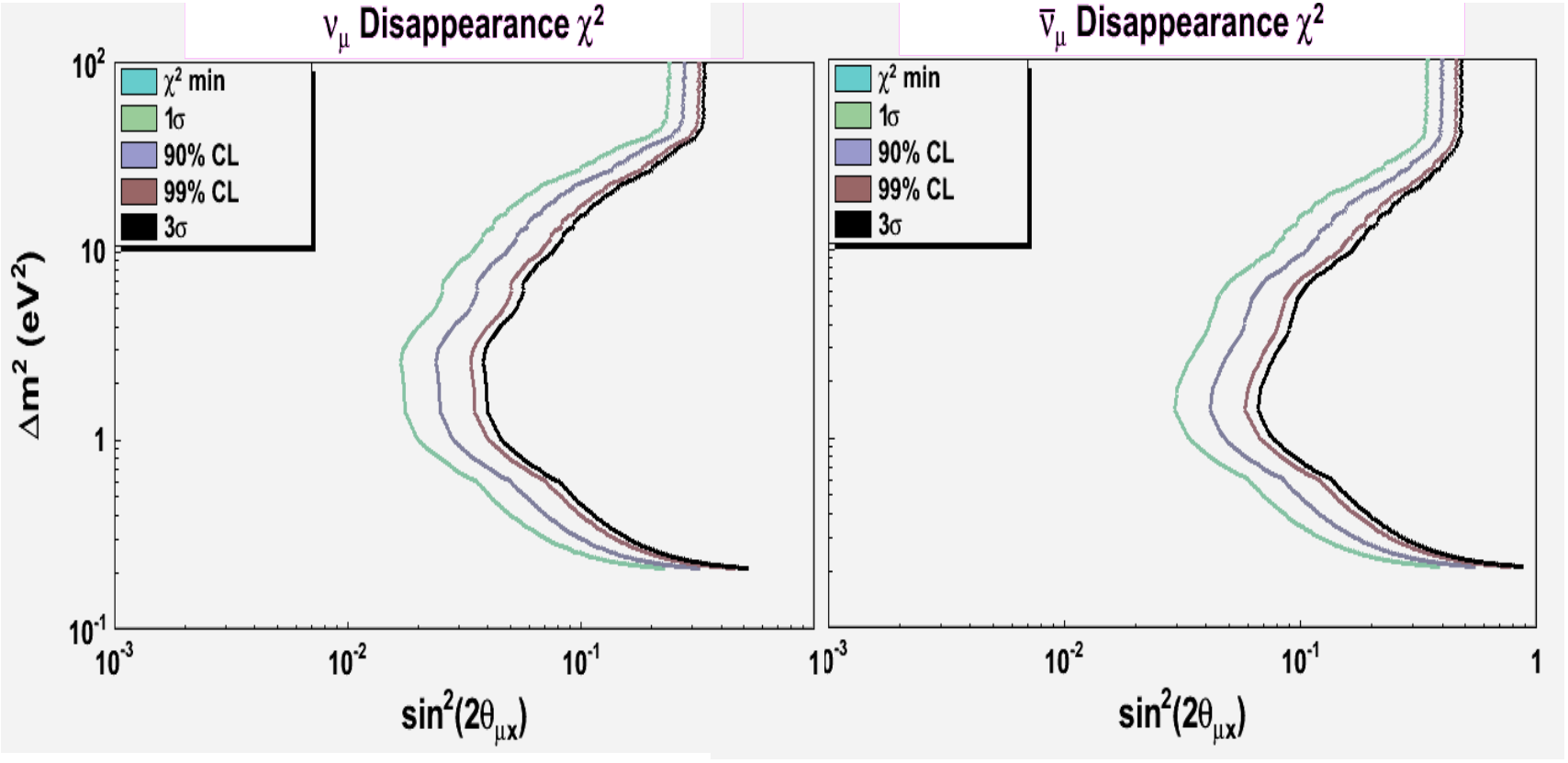


BooNE

- Better sensitivity to ν_μ ($\bar{\nu}_\mu$) disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

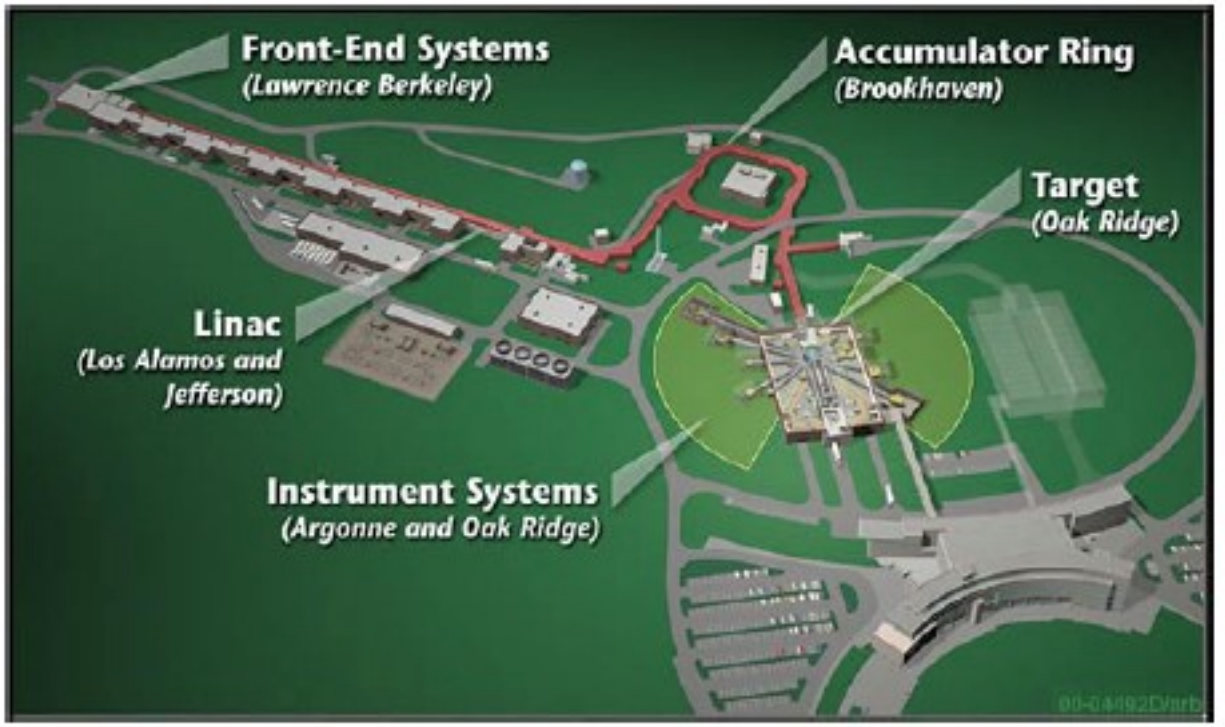
6.5e20 Far/1e20 Near POT

1e21 Far/1e20 Near POT



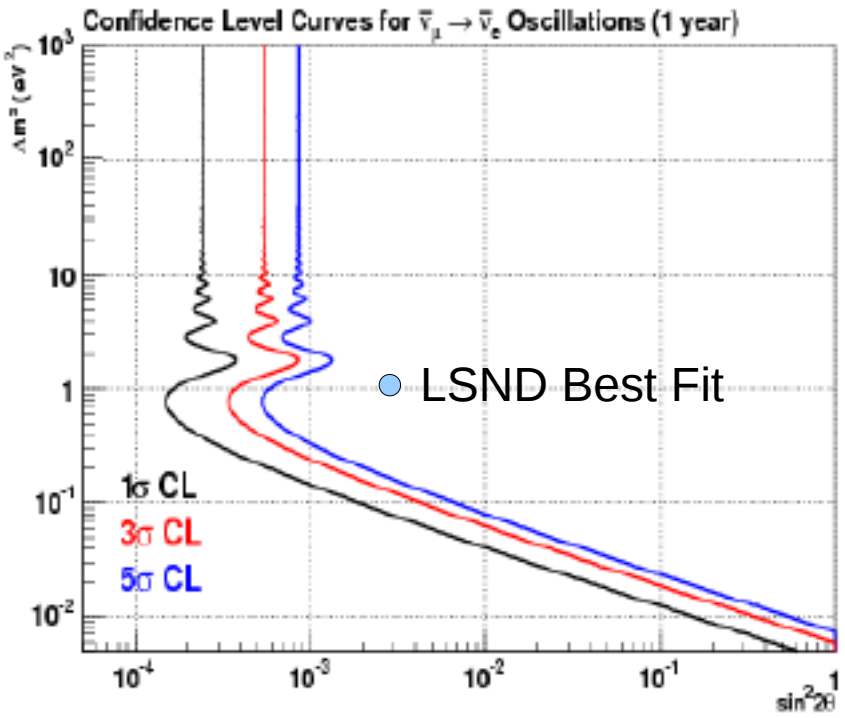
OscSNS

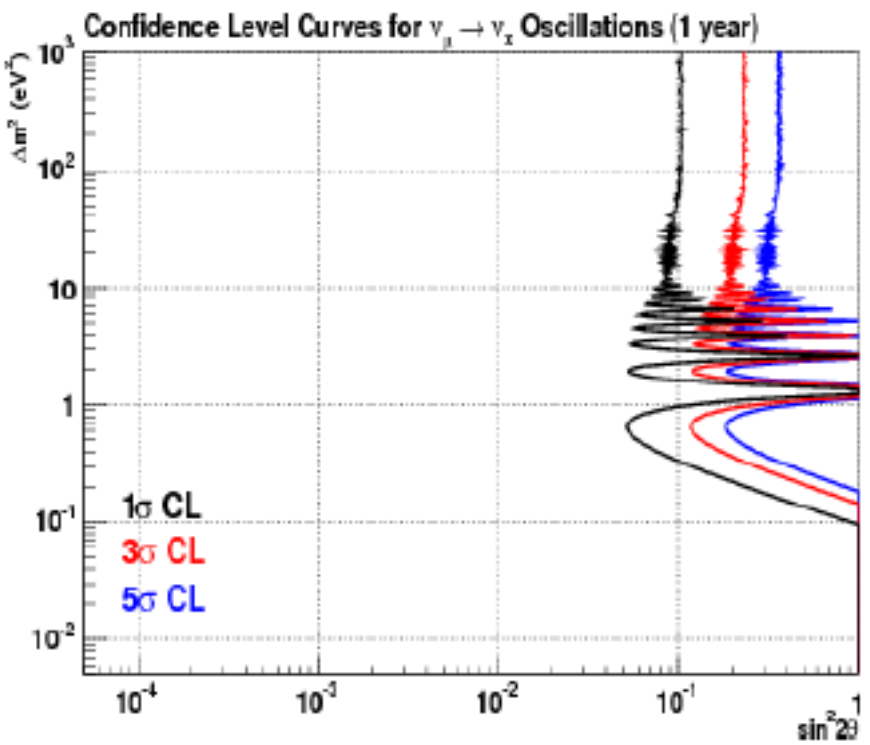
- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos



OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running



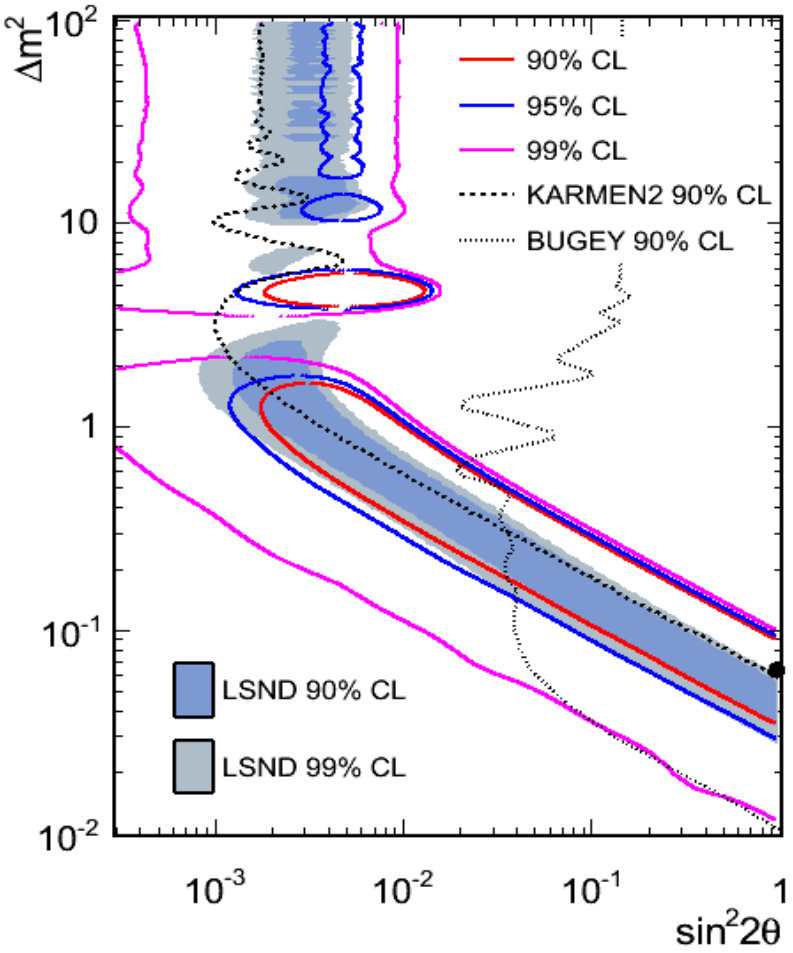


Summary

- MiniBooNE analyzed anti-neutrino data corresponding to 5.66e20POT
- See 1.3σ excess of events at low (200-475MeV) energy
- See excess of events at high (475-1250MeV) energy with absolute χ^2 probability p=3.0% for null signal (model independent)

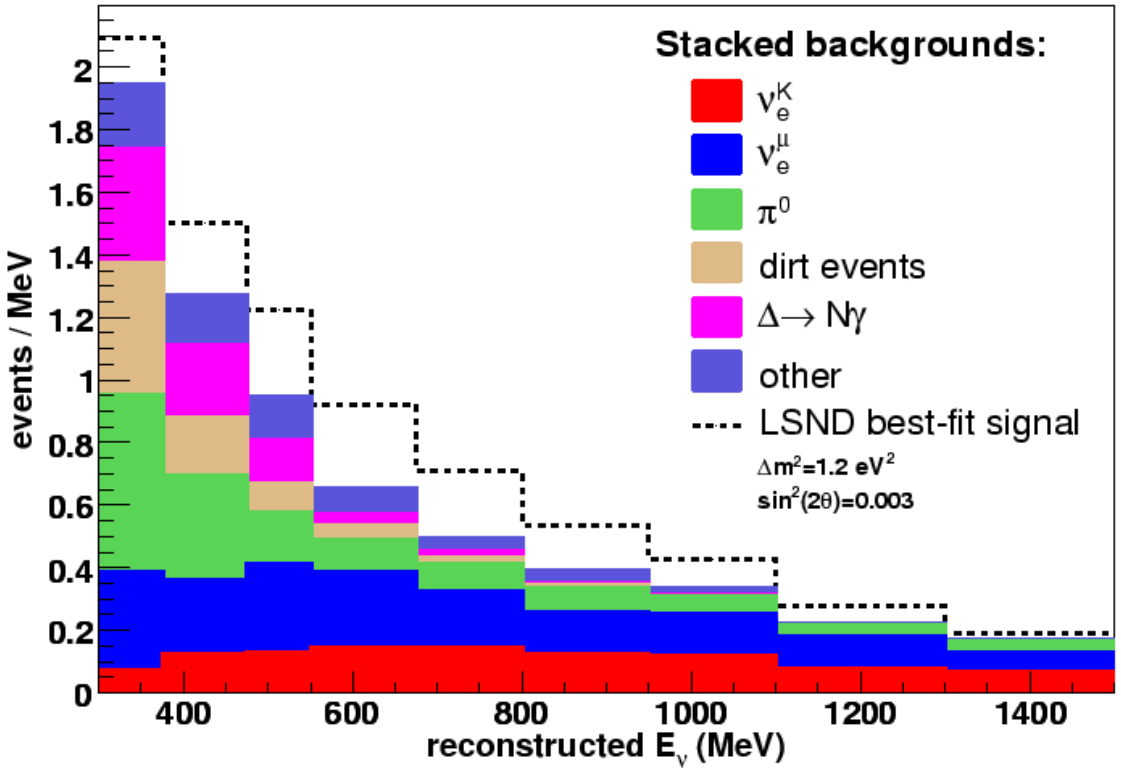
Summary

- Oscillations favored over background only hypotheses at 99.4% CL (E>475MeV)



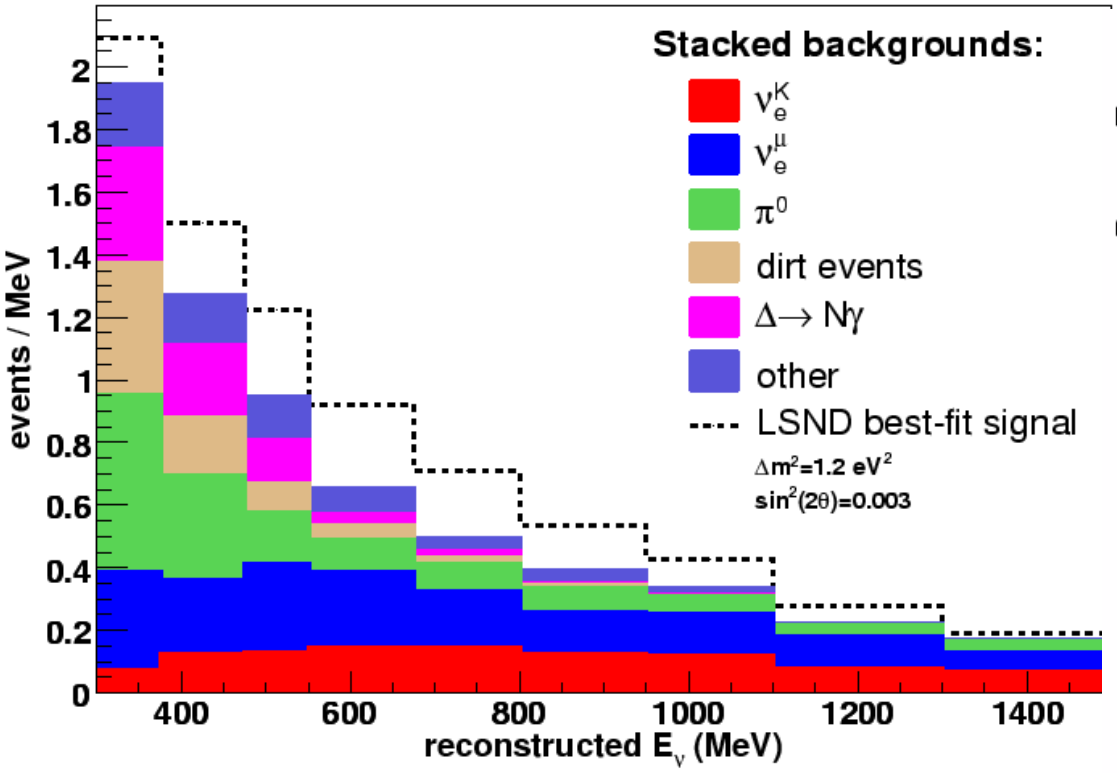
Backup

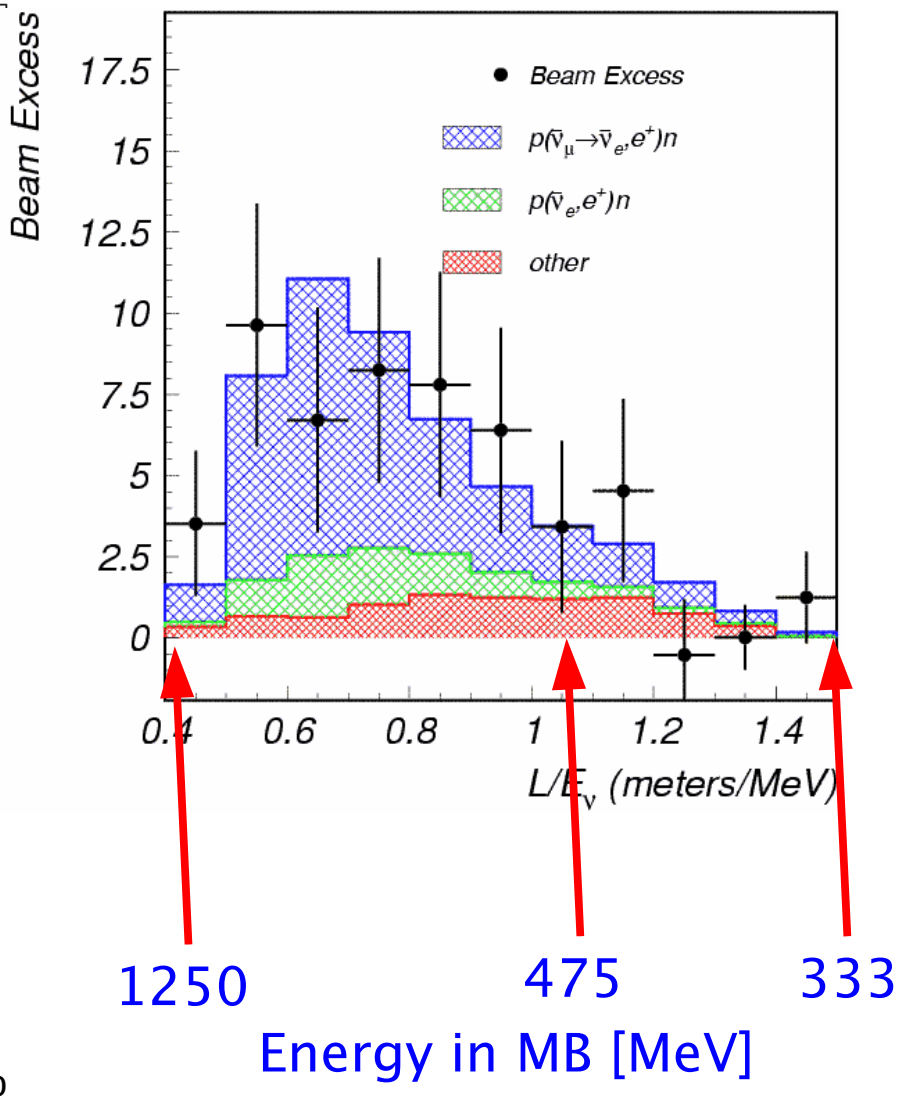
Reminders of some analysis choices



- Data bins chosen to be variable width to minimize N bins without sacrificing shape information
  - Technical limitation on N bins used in building syst error covariance matrices with limited statistics MC
- First step in unblinding revealed a poor chi2 for oscillation fits extending below 475 MeV
  - Region below 475 MeV not important for LSND-like signal -> chose to cut it out and proceed

Reminders of some pre-unblinding choices

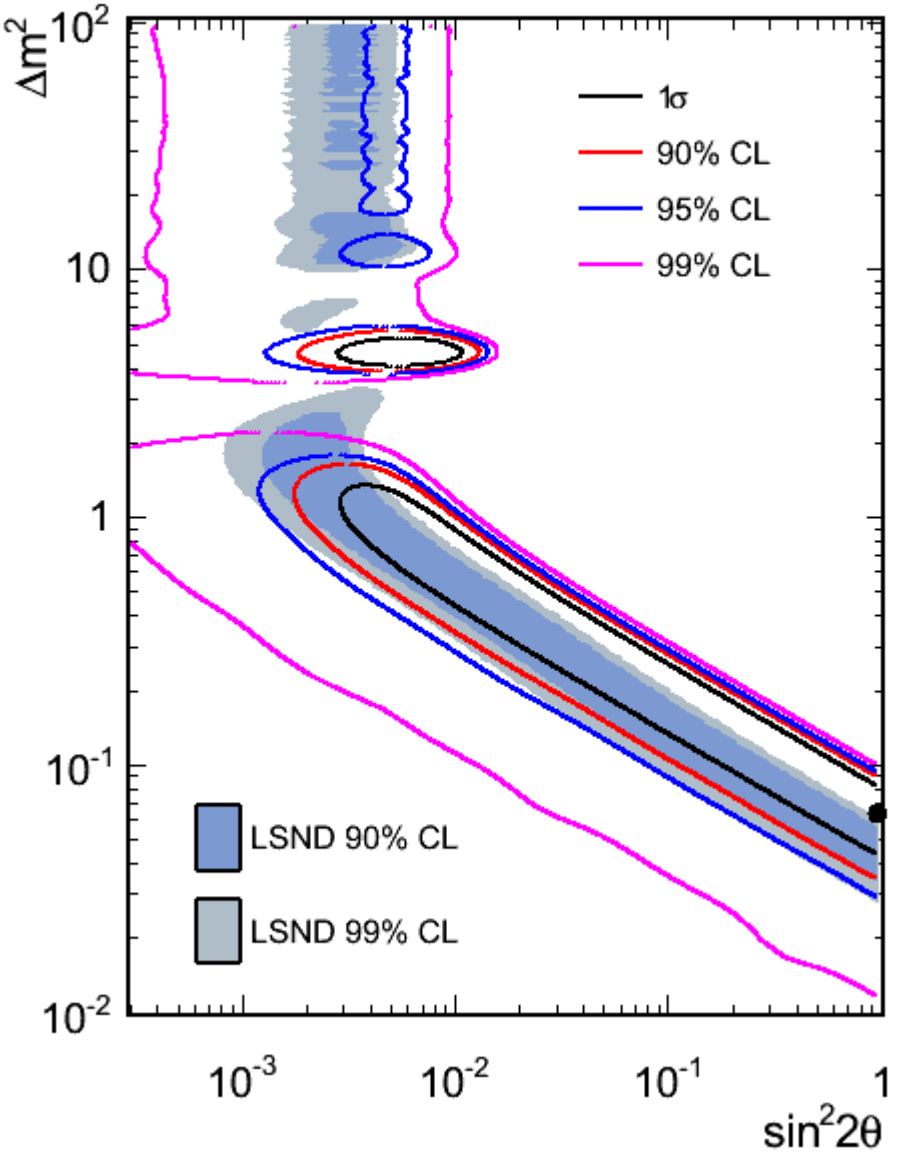




- Why is the 300-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B
  - Many systematics grow at lower energies
  - Most importantly, small S/B so not a good L/E region to look for LSND type oscillations

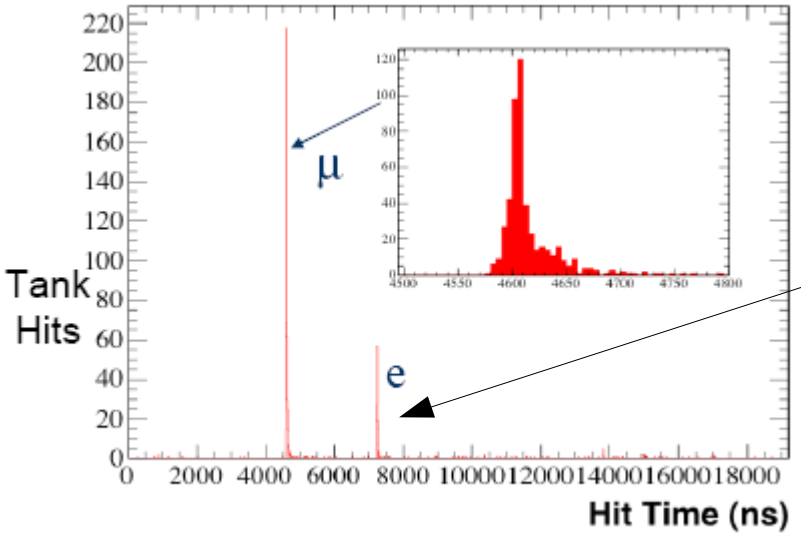
E>475 MeV

- 1 sigma contour includes $0.003<\sin^2 2\theta<1$



Subevent structure

- ν_μ CCQE have 2 sub-events separated in time
- Multiple hits in ~100ns window form a subevent



From stopped $\mu \rightarrow e+\nu_\mu+\nu_e$